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A MESSAGE REPOSITORY FOR DELAY-TOLERANT NETWORKS

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Internet technology, as well as other networking technologies, is running based on some assumptions, such as the existence of an end-to-end path between source and destination, low data loss rate, utilizing a packet-switching mechanism in communication and end devices supporting the TCP/IP protocol suite. However, these assumptions may not hold in the emerging challenged networks such as mobile ad-hoc networks. Thus, new solutions are needed to address the arising problem in challenged environments. Delay-tolerant Networking (DTN) approach is one robust way to enable communication in the environments with high delay and frequent disruption.

Due to the challenged environments, DTN nodes have limited contact opportunities to forward messages. Therefore, the message delivery ratio of DTN networks is always lower compared to that of the traditional Internet. With the intention of enhancing the network performance and increasing the message delivery ratio, we deploy a set of infrastructure nodes, which are called message repositories (MRs), into DTN networks. MRs are the normal DTN nodes with infrastructure connectivity and supporting specific message exchange mechanism. When a mobile user connects to a MR, they are able to retrieve messages which they are not hold from each other following a specific message exchange procedure.

We evaluate the performance of the MR scheme by means of simulation. We expect to figure out in which cases, and by how much the MR increases the message delivery rate and shortens the message delivery delay in DTN networks. We unitize an urban scenario with multiple environmental variables for our simulation. The most important environmental variables include underlying DTN routing protocols, the number of MRs and MRCs, node buffer size,etc. Furthermore, we compare the performance of multiple message exchange mechanisms of MR scheme in our simulation.

Keywords: Delay-tolerant Networking (DTN), Message Repositories (MRs), Message Repository Clients (MRCs), Simulations, Routing Models, Mobility Models

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Abbreviations

AA	Application Agent
ADU	Application Data Unit
AODV	Ad-Hoc On-Demand Distance Vector
ASN.1	Abstract Syntax Notation One
BPA	Bundle Protocol Agent
CLA	Convergence Layer Adapter
DoS	Denial of Service
DTN	Delay Tolerant Networking
DTNRG	Delay Tolerant Networking Research Group
EID	Endpoint Identifier
GUI	Graphical User Interface
IP	Internet Protocol
MBM	Map-Based Model
MR	Message Repository
MRC	Message Repository Client
MRG	Minimum Reception Group
ONE	Opportunistic Network Environment
POI	Points of Interest
PRoPHET	Probabilistic Routing Protocol Using History of Encounters and Transitivity
SAW	Spray and Wait Routing
SDNV	Self-Delimiting Numeric Value
SPMBM	Shortest Path Map-Based Movement Model
SSP	Scheme Specific Part
TCP	Transmission Control Protocol
UDP	User Datagram Protocol
URI	Uniform Resource Identifier

1 Introduction

Delay-tolerant networks (DTNs) are a class of networks that provide communication service under environments with long end-to-end delay, frequent partitions and sparse resources. In DTNs, end-to-end routes between the source and destination may only exist for a short and unpredictable period of time. Network partitions can be caused by limited radio range, environmental changes, low power resources or nodes breaking down. To overcome these limitations, a store-carry-forward approach is proposed for message delivery in DTNs. The transfer mode of DTNs is regarded as a hop-by-hop data transfer rather than an end-to-end data transfer. Therefore, messages are temporarily buffed in intermediate nodes and forwarded to the next hop immediately a new link becomes available.

Many emerging networks are characterized by long delay and intermittent connectivity, for instance, interplanetary networks, sensor networks and sparse mobile ad-hoc networks. Traditional Internet protocols will fail for establishing communications without an end-to-end path. DTN offers one solution to this problem [1].

The early deployment of DTNs has been in interplanetary networks, which are built to interconnect the planets in the solar system. Satellites and spaces crafts act as the nodes in the system and communicate with each other via radio. Due to the long distances, high delay, limited bandwidth and frequently disconnected links, the interplanetary system cannot be tackled by traditional Internet mechanisms [1].

Sensor networks could be utilized for environmental monitoring, including lake water monitoring, noise monitoring and earthquake monitoring. Sensors are distributed in the network with a short radio transition range and limited battery power. These sensors are unable to create a fully connected network to deliver messages to the central database. To cope with this, some data mules (like buses or boats) frequently travel around to collect data from the sensors and deliver them to a data server. For this kind of highly disconnected and long delay communication pattern, DTN is one of the effective solutions [1].

Sparse mobile ad-hoc networks could be another category of challenged networks. Link disconnection is mainly due to the mobility of nodes. Only when the nodes are within each other's radio coverage, data exchange is possible. Because of the low density of the nodes, communication opportunities are rare. Each node has to buffer messages until it comes into the radio coverage of another node. Military ad-hoc networks are the typical examples of sparse mobile ad-hoc networks. In such sparse mobile ad-hoc network environments, traditional Internet approach is inefficient. However, DTN provides one solution to the problem [1].

Low-cost communication in urban and rural areas is another instance for implementing DTN solution. In urban environments, mobile users with devices supporting wireless communication, such as mobile phones or laptops, could interconnect and share data resources. Due to the mobility of users, the contact duration between users is short. Thus, the message delivery opportunities might be low. In rural areas, there might be no infrastructure connection existing for individuals. It is possible to provide some kind of service like email with no or limited infrastructure support. Some kiosks with infrastructure connections are located in the central area of each village. Individuals could get shared Internet access by regularly contacting the kiosks [2].

1.1 Problem Statement

Let us consider a scenario of a DTN messaging application in an urban scenario. Mobile users move around an urban area and are frequently in contact with each other. Each user carries a device, such as a mobile phone or PDA, enabled with the DTN messaging application. User devices will create messages that might be large but not urgent for delivery. When users meet, they will exchange messages with each other via short-range radio such as WiFi. These transferred messages are buffered in the storage of user devices until the next hop is available. Due to the spare density of the mobile nodes, limited radio coverage and battery power of the mobile devices, the message delivery ratio of the DTN messaging application is not satisfying compared to that of the traditional Internet. For this reason, we propose to deploy a set of infrastructure nodes in mobile ad-hoc networks. We call such Internet-connected nodes message repositories (MRs) [3].

MRs hold all the functions of the normal DTN nodes. In addition, MRs support infrastructure connectivity and provide a specific message exchange mechanism. When an MR-aware node connects to MR, they will inform each other of the messages they are currently holding by exchanging their message lists. Then, they will retrieve the messages they do not have from each other. The MR-aware nodes are called Message Repository Clients (MRCs). Different from MRCs, normal DTN nodes only exchange messages with MR only following the underlying DTN routing protocol. MRs are always equipped with a database located in the infrastructure network. Multiple MRs in one area share a single database. Mobile users could retrieve targeted messages from MRs via either DTN or Internet. MRs are stationary or mobile around the places which mobile users frequently visit. When mobile users connect to the MR, they are able to exchange messages via wireless connections. In this way, MR could collect messages into the database and wait to deliver them to their final destinations. Furthermore, when mobile user access the Internet, they could also exchange messages with MR and retrieve the messages targeted at themselves via Internet. A network administrator is able to manage the repository database via Internet as well. Figure 1.1 shows the overview of the message repository scheme [3].

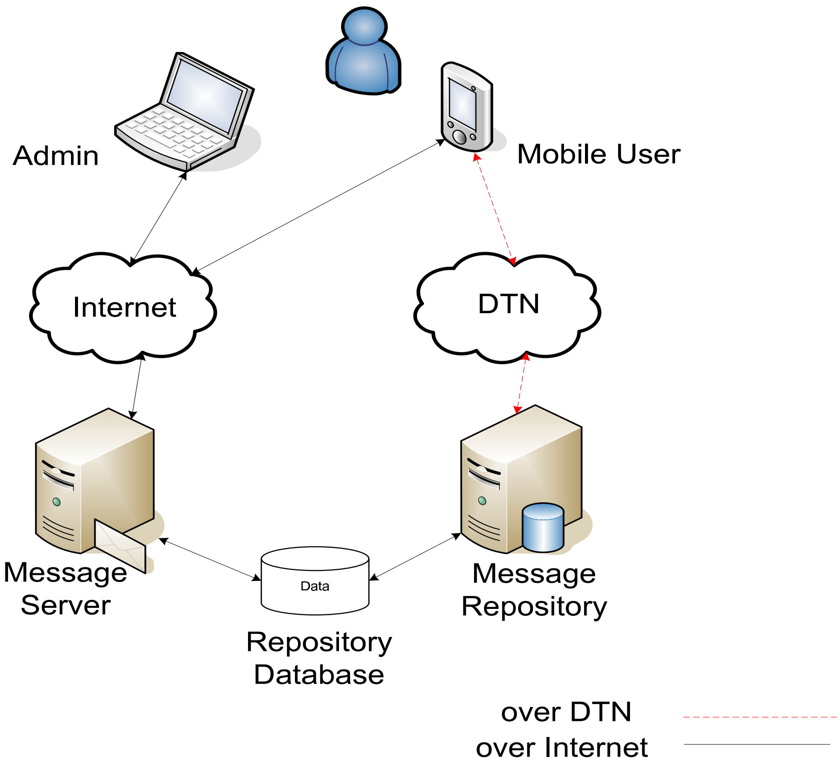


Figure 1.1: Overview of Message Repository

In the thesis, we run the simulation of the MR scheme under multiple environmental variables (mobility models, routing protocol, buffer size of mobile devices, etc.) in an urban scenario. We expect to find out how much, and in which cases, the MR will increase the message delivery rate and shorten the message delivery delay. Moreover, a comparison is made of different MR message exchange patterns in order to figure out which one gives the best performance.

1.2 Goals and Scope

The main goal of the thesis is to evaluate the performance of MRs when applied in urban environments by means of simulation. Firstly, we perform a literature study of the approaches relating to MRs from the perspectives of deployment goals, architecture, discovery approaches and communication procedure. Then, we will analyze the performance of MRs in DTNs. The most important performance metrics we are focusing on are message delivery rate, message delivery delay and node buffer occupation ratio. In addition, we expect to investigate the ratio of message delivery over DTNs to over Internet. The MR design is evaluated by deploying them in the urban scenario with various environmental variables. The possible environmental variables are MR message exchange procedure, underlying routing algorithm, the number of MR and MRC nodes, buffer size of mobile devices and the status of MR (stationary or mobile).

In this thesis, we focus on evaluating the MR performance based on simulation outcomes. Issues related to the real-world implementation of MRs, however, is beyond the scope of this work.

1.3 Related Work

The concept of message repository is proposed in [3]. The system architecture, message exchange procedure, expected practical goals and basic implemented MR prototype which extends the DTN2 stack have also been elaborated in [3].

Before proposing the message repository, Wenrui Zhao et al. have raised the ideas of throwboxes and message ferries. Similar to MRs, these two approaches seek to introduce relay nodes into a DTN network and increase the message delivery ratio [5][6].

Throwboxes are deployed to create more contact opportunities in DTNs. Throwboxes are small stationary nodes with a wireless interface and limited buffer size. They act as relays between mobile nodes to enhance the capacity of DTNs. Throwboxes will never be sources or destinations and never interconnect with themselves [5].

Message ferries are a set of mobile nodes that introduce the non-randomness characteristics to the mobility of nodes. Such non-randomness facilitates data delivery and provides more communication opportunities in DTNs. The role of message ferries is to periodically visit and relay data among distinct nodes in sparse networks. The message ferrying approach introduces a new routing policy in DTNs [6].

Both the message repository and throwboxes approaches use the additional stationary or mobile nodes to increase contact opportunities and message delivery ratio. Nevertheless, in the message repository scheme, the MR and MRC nodes treat each other as special nodes to exchange message lists and retrieve intended messages following a specific message exchange procedure. Throwboxes are not regarded as special nodes. Similar to the MR scheme, normal nodes are aware of message ferries as special nodes. However, this message ferrying scheme introduces a new routing policy. With message ferry as a relay, it is possible to achieve an end-to-end message delivery. In contrast, a message repository scheme only adds a complementary component to the current DTN routing policy [3][5][6].

Another related work is KioskNet which deploys kiosks as infrastructure nodes to provide shared Internet connections in rural areas. KioskNet and our MR scheme share the same idea of supporting low-cost Internet access via infrastructure nodes. Cars are utilized to collect data from home to the nearest kiosk. Similarly, messages coming from the Internet will be delivered from kiosks to the targeted home by car. The common goal of our approach and KioskNet is to enable shared Internet access for individuals in rural areas. The difference is that KioskNet focuses on village-Internet communications while the MR approach emphasizes both intra-village and inter-village communications. In addition, the message repository approach supports a management interface function, by which a network administrator could search, monitor and modify the MR database [3][7].

Essentially, the concept of the message repository also shares the same idea of the traditional Internet email box which acts as a rendezvous point for message storing and distribution. A sender deposits messages in there and the receiver retrieves messages addressed to himself when conditions permit. Similarly, a mobile IP home agent follows such a function at the individual packet level. A mobile IP home agent maintains the registration list which identifies the binding foreign agents of the mobile nodes. It works as a proxy of the mobile node. Anyone who wants to send a message to the mobile node needs to transfer the message to the mobile IP home agent. Then, the mobile IP home agent will forward the message to the corresponding foreign agent [3].

Nevertheless, the message repository goes beyond this concept because there is no continuous connectivity required. The infrastructure network serves as a complement to the intermittent connection for the message repository scheme.

1.4 Organization

This thesis has been divided into six chapters. In Chapter 2, we introduce the background of the DTN architecture, the bundle protocol, mobility models and routing algorithms. Chapter 3 includes a discussion of the message repository scheme in theory, including the architecture, expected goals, requirements and communication procedures. Chapter 4 introduces the tool for the simulations undertaken in this work. The software architecture and basic functions of the ONE simulator are described briefly, giving readers the theoretical background to the simulations contained in the following chapter. In Chapter 5, the MR design is evaluated by means of simulation. We run the simulation under different simulation cases with multiple environmental variables. We analyze the results and evaluate the performance of MRs based on certain performance metrics. In the final chapter of the thesis, we draw the conclusions and put forward a proposal for further work.

2 Background

Internet technology, as well as other networking technologies, is running based on some assumptions, such as the existence of an end-to-end path between source and destination, low data loss rate, utilizing a packet-switching mechanism in communication and end devices supporting the TCP/IP protocol suite. Some emerging networks such as interplanetary networks and sensor networks do not conform to those assumptions. Such networks are involved in challenged characteristics, including intermittent connectivity, long delay, limited power resources, etc. Traditional Internet solutions often break down in challenged networking environments. For example, the Transmission Control Protocol (TCP) requires three-way handshake for establishing a connection. This simply cannot be achieved in frequently partitioned network environments. Therefore, the architecture and protocols of challenged networks might deviate from the traditional Internet protocols [8][9].

2.1 DTN Architecture

The Delay Tolerant Networking Research Group (DTNRG) has specified the DTN architecture. Networks implementing the architecture can be called DTNs for short. The DTN architecture is applicable for occasionally connected environments with long delay and high error rates. The DTN architecture was originally developed for an interplanetary network, which is an Internet-like system with high communication delay, and aims to provide services for space exploration. Recently, the DTN architecture has been found to be applicable in various common environments, such as sensor networks, terrestrial wireless networks and underwater acoustic networks. The DTN has a bundle overlay architecture built on top of multiple regional networks with distinct network characteristics. Whatever lower-layer technologies are utilized, the bundle layer will provide a persistent and integrated interface to applications. Figure 2.1 depicts the DTN architecture proposed by the DTNRG, which includes application layer, bundle layer, convergence layer and underlying link layer [8][10].

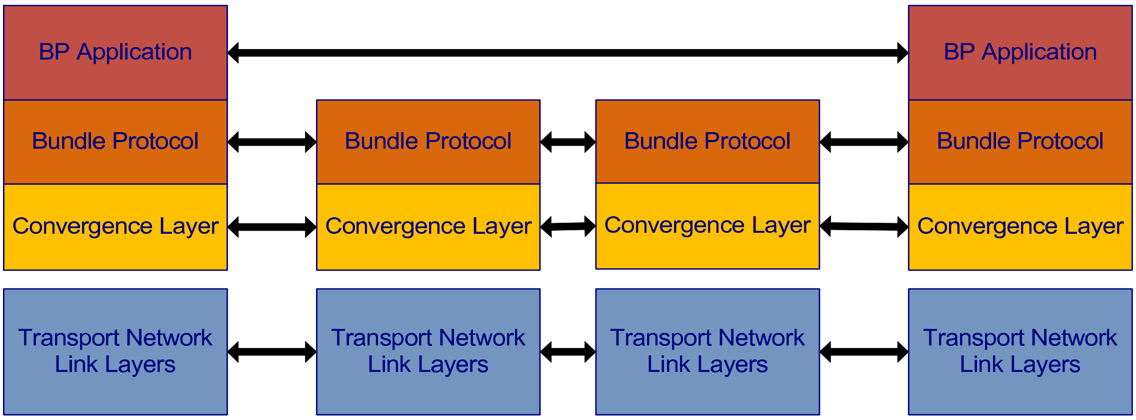


Figure 2.1: DTN Architecture

The DTN architecture operates over heterogeneous link layers. The convergence layer acts as an adaptive layer and maps the bundle protocol to the lower-layer network. The convergence layer has link layer protocol-specific properties. The function of the convergence layer should adapt to the link layers. Several protocol-specific convergence layers, for instance, the TCP convergence and User Datagram Protocol (UDP) convergence layers, are specified. The convergence layer provides an integrated and consistent interface to the bundle layer [4][8].

A. Bundle Communication

In DTNs, a message delivered over the bundle layer is known as a bundle. A bundle is composed of three parts: a source-application's user data, control information and a bundle header. Like user data, the length of a bundle can be arbitrary.

Applications running on top of the DTN architecture exchange data in an arbitrary length message, which is called an Application Data Unit (ADU). ADUs are passed to the bundle layer and encapsulated into bundles for transmission. Bundles are forwarded hop-by-hop over intermediate DTN nodes in a store-carry-forward manner. Bundles are stored in the node's buffer and wait in a queue until the situation permits further forwarding. In this way, the storage system of DTNs is distributed in every single node. The distributed storage approach is sufficient and effective in the network environments with frequent partitions [8]. The bundle protocol will be described in detail in Section 2.2.

B. Custody Transfer

The DTN architecture specifies the bundle delivery options that guarantee the reliability of hop-by-hop delivery. For instance, when an application sends ADUs to the next hop, it could request custody transfer. Custody transfer is a node-to-node retransmission mechanism. DTN nodes are expected to utilize persistent storage such as a hard disk, for bundle storage, when implementing custody transfer. Hence, bundles are saved in storage even if the network fails or the system reboots. Intermediate DTN nodes which take care of custody transfer are called custodians. When a custodian sends a bundle, it requests custody transfer for the next hop. If the next hop node accepts this custody transfer request, it will reply with a custody acceptance acknowledgment and becomes a custodian node for this bundle. If no acknowledgment is returned before the sender's acknowledgment timer expires, the sender will resend the bundle. Custodian nodes must store the bundle until it relays the bundle to the next custodian as long as the bundle is not expired. Custody transfer, however, cannot guarantee the reliability of end-to-end delivery [8][11].

Nodes in a DTN are not compulsory to operate with custody transfer. Nodes have the right to choose to become the custodian of a bundle or not, depending on the specific policy in use at the node [8].

C. Class of Service

The DTN architecture offers prioritized classes of services for delivering ADUs. Classifying ADUs into different priorities reflects the application's desire of the delivery urgency. ADUs are encapsulated into bundles at the bundle layer. Bundles are prioritized regarding application requirements. There are three classes of priorities defined. The bulk class has the lowest priority, the following is normal class, and the expedited class holds the highest priority [8].

The transfer priority of bundles is defined with regard to the same source. For distinct sources, bundles with expedited priority of one source are not necessarily delivered with better service than bundles with normal priority of other sources.

D. Endpoint Identifiers (EIDs) and Registrations

EIDs are used to identify the endpoints. ADUs are encapsulated in bundles and delivered based upon the EID of the destination node. A single EID may refer to multiple DTN nodes while one DTN node can be identified by more than one EID. Each DTN node at least needs one EID to address itself. A bundle is considered to have been delivered successfully when it reaches the minimum subset of DTN nodes which belong to the same DTN endpoint. The minimum subset is called the minimum reception group (MRG). When the MRG includes only one DTN node, the transfer mode is called unicast. Accordingly, when the MRG consists of any node in a group, it corresponds to anycast. When the MGR contains multiple nodes in a group, it refers to multicast [8].

The syntax of EID follows the Uniform Resource Identifier (URI) specification. There is no restriction on the URI scheme name for the DTN. The first part of the EID is the scheme name and the following part is the Scheme-Specific Part (SSP).

$$< \text{scheme name} > : < \text{scheme specific part} >$$

Currently, there are no unified naming conventions for the EID of DTN applications. The DTN2 reference implementation simply chooses ‘dtn’ as the scheme name for the EIDs [12].

The process of binding an EID to a specific application instance is called registration. With registration, the ADUs addressed to the EID could be delivered to the targeted application.

In the traditional Internet, name-to-address mapping always happens before packets are sent. This kind of address resolution is known as early binding. In contrast, the DTN architecture utilizes late binding for address resolution. Binding the destination to the EID does not necessarily happen at the source, but can be done during transmission along the path. Late binding has advantages over early binding in networks with frequent partitions. The transit time of bundle is relatively long in intermittently connected networks, possibly exceeding the validity time of binding at the source. Nodes further along the path might have more information about the binding. Therefore, a name-to-address mapping mechanism is impractical at the start of communication in DTNs [8].

E. Fragmentation

The bundle layer is permitted to break a bundle into fragments in order to improve the efficiency of bundle transfer, which is similar to the Internet Protocol (IP) layer breaking IP packet into fragments. The purpose of fragmentation is to utilize the contact capacity effectively and avoid retransmission caused by incomplete bundle transfer [8][10].

There are two sorts of bundle fragmentation, proactive fragmentation and reactive fragmentation. For proactive fragmentation, a DTN node is able to predict the downstream contact capacity. Hence, it will fragment the original bundle into multiple parts in advance. In this case, the sender node holds multiple fragments and transmits them when possible. Reactive fragmentation covers the case that a lower layer indicates a bundle was only partially transferred. The missing portion will be retransmitted by the sender node [8].

In both cases, the reassembling of fragments occurs at the bundle layer of the final destination. Like IP fragmentation, fragments can be further fragmented for both proactive and reactive approaches. Moreover, any DTN node along the route is allowed to fragment the passing bundles. If a bundle should not be fragmented, a 'do not fragment' flag can be set to prevent fragmentation.

2.2 Bundle Protocol

The bundle protocol operates at the bundle overlay that may be running on top of regional networks in highly stressed environment. DTN nodes require three components to implement the bundle protocol. As shown in Figure 2.2, the Application Agent (AA) utilizes the bundle protocol service to enable communications regarding the desire of the application. The Bundle Protocol Agent (BPA) executes the bundle protocol. The Convergence Layer Adapter (CLA) implements the convergence layer function to integrate the BPA to the underlying networks.

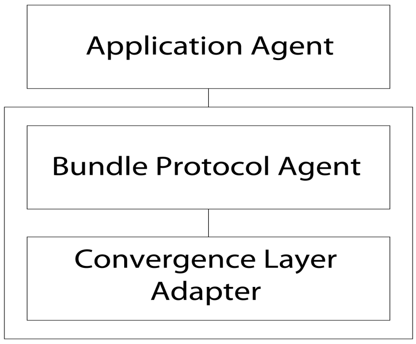


Figure 2.2: Components of the DTN Node

The concepts of the EIDs, bundle transfer service and fragmentation, which are included in the bundle protocol operation, have been illustrated in the previous section. In this section we will focus on the bundle blocks defined by the bundle protocol.

Numeric fields in bundle blocks are encoded by self-delimiting numeric value (SDNV) scheme. SDNV is a particular encoding approach to encode non-negative numeric values. The numeric field using SDNV notation can be of variable length [1].

2.2.1 Bundle Blocks

A bundle is composed of blocks, of which there are three categories: primary block, extension block and payload block. The primary block is a mandatory and basic block of a bundle. The basic information of a bundle is encoded in the primary block. Figure 2.3 depicts the primary block of a bundle [15].

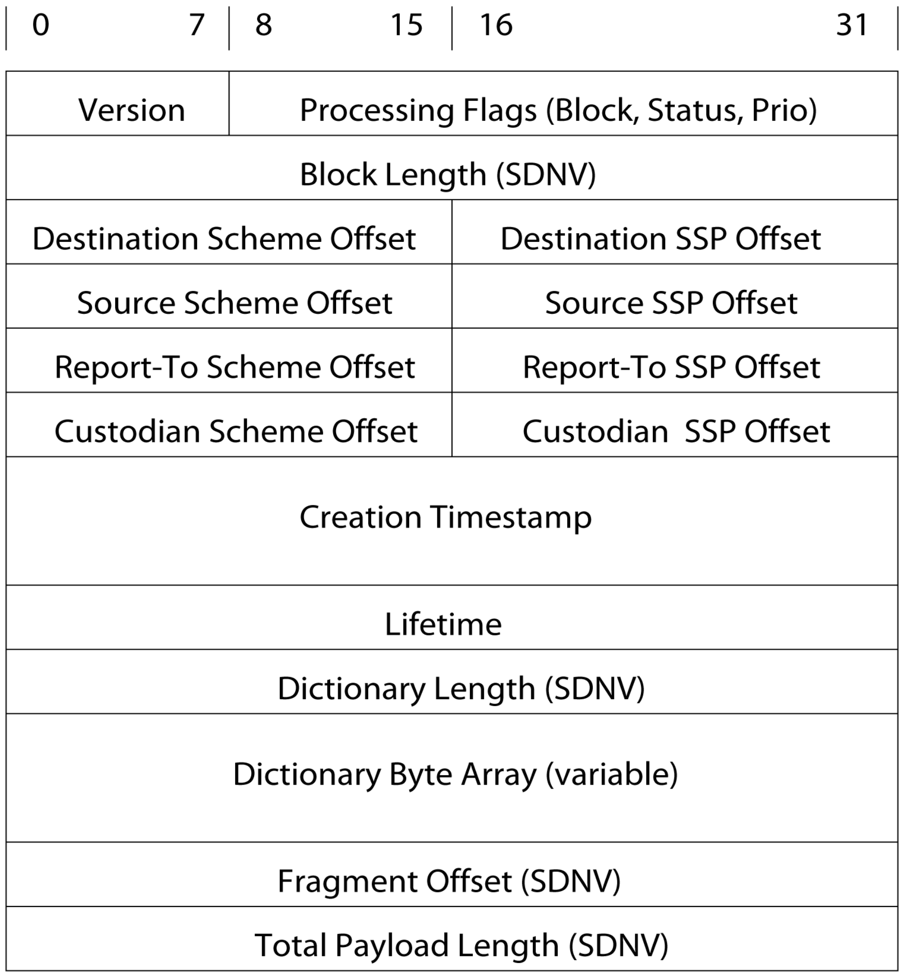


Figure 2.3: Bundle Primary Block

Version: the version filed is only 1 byte in length and represents the version of the bundle protocol.

Bundle Processing Control Flags: these flags indicate the block processing information, priority service class and bundle status reports options.

Block length: the block length field shows the length of the remaining parts of the block in the SDNV notation.

Offset: there are multiple offset fields in the primary block, including destination scheme offset, destination SSP offset, source scheme offset, source SSP offset, report-to scheme offset, report-to SSP offset, custodian scheme offset and custodian SSP offset. Those fields indicate the corresponding EIDs offsets in the dictionary byte array.

Creation Timestamp: the creation timestamp refers to the bundle's creation time. The fields of creation timestamp, source EID, fragment offset and payload length can together uniquely identify a bundle.

Lifetime: the lifetime field identifies the active lifetime duration of a bundle in the network. If the current time exceeds the creation timestamp plus the lifetime of a bundle, the bundle will be deleted by the DTN nodes.

Dictionary Length: this field shows the length of the dictionary byte array in the SDNV notation.

Dictionary Byte Array: this field defines a byte array which contains the EIDs utilized in the primary block. EIDs could be located by the corresponding offsets. The most significant advantage of this approach is to efficiently handle long EIDs strings and repeatedly use the same EIDs.

Fragment Offset: if a bundle is a fragment, the fragment offset indicates the fragmentation starting point in the original ADU. The fragment offset field uses the SDNV notation.

Total Application Data Unit Length: if a bundle is a fragment, this field indicates the length of the original ADU which the bundle is fragmented from. This field also utilizes the SDNV notation.

The bundle payload block contains the real bundle content, the ADU. Figure 2.4 shows the fields of the bundle payload block [15].

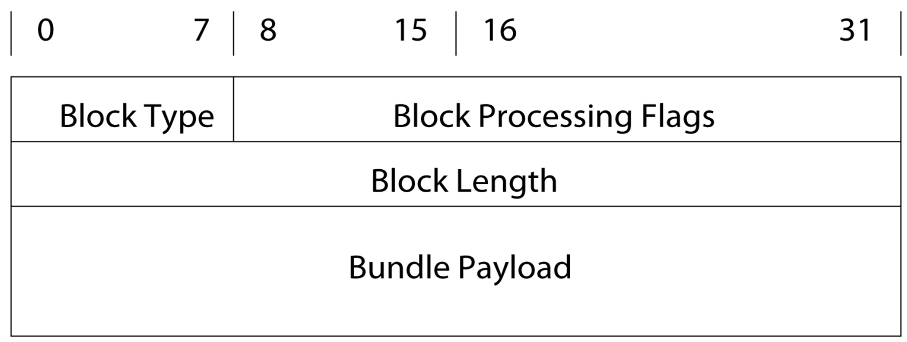


Figure 2.4: Bundle Payload Block

Block Type: the block type field indicates the block type. Value 1 indicates the payload block.

Block Processing Control Flags: this field is used to select block processing control options. For instance, it could be set to delete a bundle if a block cannot be processed, or a block is forwarded without being processed.

Block Length: this filed is identical to that in the primary block and shows the length of the remaining parts of the block in the SDNV notation.

Payload: payload field contains the ADU of the bundle.

Extension blocks include all of the other blocks, except the primary block and payload block. There are no unified specifications for the extension blocks. It is possible that some DTN nodes are unable to process certain extension blocks generated by other nodes [15]. The format of extension blocks is shown in Figure 2.5 and Figure 2.6.

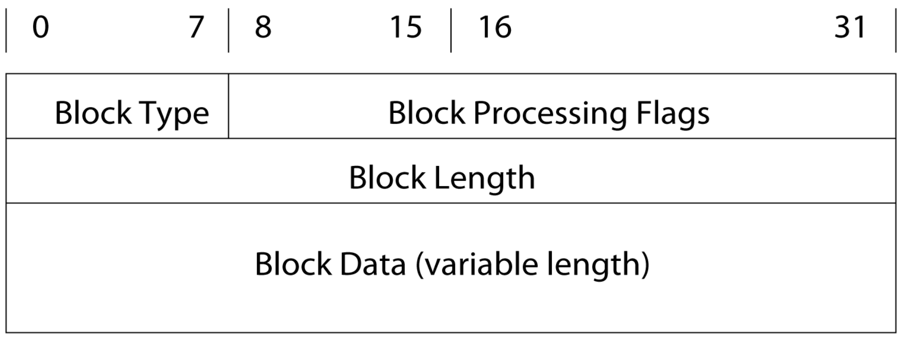


Figure 2.5: Extension Block without EID Reference

Security-specific bundle blocks belong to the category of extension block. Currently, there are a great number of potential threats existing in DTNs. DTN applications are vulnerable to threats, such as masquerading, replay attack, denial of service (DoS) and traffic storm. To protect DTN application from those threats, the DTN architecture adopts both hop-by-hop and end-to-end security mechanisms. Those mechanisms are accomplished via the use of security-specific bundle blocks.

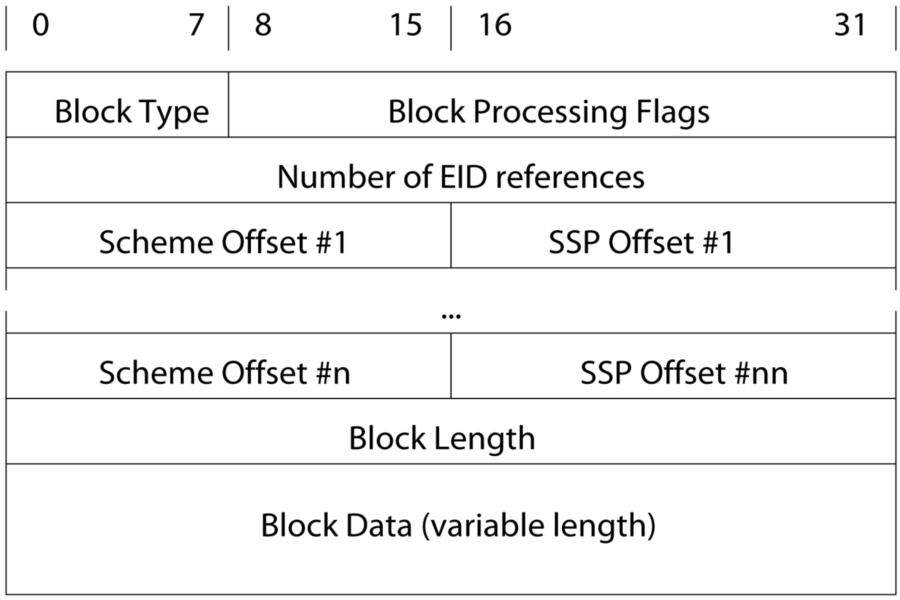


Figure 2.6: Extension Block with EID Reference

A bundle authentication block is utilized to insure the authenticity of bundles along intermediate nodes. It provides a hop-by-hop authentication mechanism. A payload security block provides an end-to-end authenticity protection between security-source and security-destination. Intermediate nodes along the path may have the right to verify the payload security block. Hence, it is possible to set a gateway node with the policy to drop the bundles with an incorrect payload security block. A confidentiality block is to encrypt some parts of a bundle between the security-source and security-destination. Both payload and other blocks could be encrypted [1][13][14].

2.2.2 Convergence Layer Protocols

The DTN architecture aims to provide communication in a wide range of underlying networking environments. However, underlying networks always implement distinct low-layer protocols. The convergence layer will provide an integrated and consistent interface to the bundle layer. The convergence layer operates in a protocol-specific manner, which means the convergence layer provides different solutions towards different underlying protocols. Several protocol-specific convergence layers are specified, for instance, the TCP convergence layer (TCPCL) and UDP convergence layer. Every convergence layer provides the basic services for the bundle overlay as follows.

- Sending and receiving bundles to and from neighbor nodes when contact is established.
- Connection management.

As TCP is stream-oriented, it does not define the boundary for application data. Therefore, the TCP convergence layer has the function to mark the bundle boundary. The bundle is encapsulated into segment with a minimal overhead at the TCP convergence layer. The TCP convergence layer protocol supports to detect the connection and transmission status, such as the link going up and down, and bundle delivery. The TCPCL also defines the messages for application-level acknowledgements, regular keep-alive and tearing down of a connection [16].

2.3 Mobility Models

The mobility models of DTN nodes have a strong impact on the performance of DTN routing protocols or applications. Therefore, we need to obtain and utilize different mobility models to evaluate the performance of DTN-based applications. However, it is difficult and impractical to obtain all the DTN mobility models from real-world mobility traces. Therefore, researchers summarize the characteristics of real-world traces and abstract synthetic mobility models to characterize node movements. For pedestrians, basically there are two categories of mobility models, the entity mobility model and group mobility model.

The entity movement models include random walk, random waypoint, random direction and map-based mobility, etc. Take random waypoint for instance, a node chooses a random intended position and moves toward it at random speed. When the node reaches the destination, it will pause for a while then choose a new targeted destination and repeat the previous procedure. The random waypoint model is simple and easy to implement, but it does not reflect the actual mobility properties. In map-based mobility, mobile nodes move within a predefined movement area and towards the preferred positions. In map-based mobility, we can also schedule the movement of the vehicle such as buses or cars, by a predefined route in the map [17].

The group mobility models illustrate scenarios that a group of mobile nodes follow an identical mobility pattern. Some typical group mobility models are column mobility model, nomadic community model, pursue mobility model and reference point group mobility model [17][18].

Our research group has proposed a working day movement model that attempts to represent the everyday life of people. In this model, people go to work in the morning, work during daytime, return home or do other activities in the evening. The working day movement model combines many different characteristics of entities and activities and reflects human activities in real-world environments [19].

2.4 Routing Protocols

Routing in spare mobile ad-hoc networks is a challenge since contacts and time duration are not known in advance. In the challenged environments, traditional ad-hoc routing protocols such as Ad-hoc On-demand Distance Vector (AODV) routing often fail to establish the routes [20].

There is only a single copy for each message in traditional routing mechanisms. However, single message copy method is not applicable to DTN routing. It might take a long time for delivering the single message copy to its destination in the challenged networking environments due to the limited contact opportunities. It is high possibility for the message copy to be lost or time out on its way to the destination. Message delivery rate might be low in spare mobile ad-hoc networks compared to that in the traditional Internet. To improve this situation, various DTN routing protocols give a common solution, that is to replicate message copies. With multiple copies for a single message, messages could get more chance of being delivered to the final destinations. Currently, the challenge for the DTN routing protocol is to determine whether a DTN node should transmit a message copy to anther node when they encounter each other. Some well-defined DTN routing protocols will be illustrated in the following [21][22]:

In direct delivery routing, DTN nodes keep waiting to forward the message until they meet the message's final destination. In this routing protocol, only a single copy of each message in present in the network. The source node will keep the message until the message is expired. Therefore, messages are prone to be lost and delivery probability is quite low [21][23].

In epidemic routing, DTN nodes try to distribute all the messages to all other nodes. Messages are forwarded in a random order until the contact between nodes goes down or both nodes hold all the messages. As the epidemic routing algorithm is willing to replicate messages as much as the nodes number in DTNs, it will cause high overload of the nodes's buffer. When a node's buffer becomes full, it drops the oldest message to make space for new coming messages. Due to the frequency of message transfer and deletion, the power resource consumptions of mobile devices will be another challenging issue [23][24].

In the Spray and Wait (SAW) routing protocol, a mobile node distributes a certain number of message copies to other nodes until it holds only one copy of each message. Then, the node waits to deliver the messages to the final destinations. There are two modes of SAW routing, normal and binary. In normal mode, the node initially creates N copies of messages and transmits one copy to the first N-1 nodes it meets. The node stops transmitting until it holds only one copy itself. In binary mode, the node initially holds N copies of a message. Every time the node meets others, it will transmit half holding copies of the message to the new node. Eventually, the node will hold only a single copy of the message then it waits to deliver the message to the final destination. The binary mode is recommended since it is optimal in terms of message distribution [25][26].

Different from the previous routing protocols we mentioned, the Probabilistic Routing Protocol using History of Encounters and Transitivity (PRoPHET) routing protocol tries to exploit the non-random movement and make a routing decision according to the historical encounter probability of mobile nodes. This protocol assumes that, if two nodes encounter several times, it is more likely for them to meet again. When two nodes meet, they will exchange their 'prediction' for reaching the destinations of certain messages. A message will be relayed to the next hop only if the new node has a higher prediction of meeting the recipient of the message. If the mobility pattern of nodes is like what PRoPHET assumed, this routing algorithm will be efficient to make accurate message delivery. In PRoPHET routing there is no limitation on the copy number of each message. Messages will be replicated and forwarded to the next node based on the routing algorithm calculation. However, routing decision calculation of PRoPHET will cost more energy than that of simple forwarding routing protocols [27].

The MaxProp protocol is another routing protocol based on historical encounters. The delivery rule of MaxProp is to deliver messages of high delivery prediction with high priority. If there are N nodes in the network, initially each node will set vectors to be 1/N-1 for the other N-1 nodes. The value stands for an equal encounter probability of other nodes in the network. When two nodes meet, they will firstly exchange and update the encounter probability vectors. With the vectors, nodes could calculate the shortest path to each particular destination using Dijkstra's algorithm. The path cost is based on the value of the encounter probability vectors. The higher the vector value, the higher the probability for message delivery and the lower the cost of the path will be. Messages are ordered by destination path costs. Messages being transferred and dropped will follow this order. The routing calculations of the MaxProp protocol are complex and cost much energy [28].

Even though several approaches have been proposed for DTN routing, each of them may only perform well under specific environmental conditions. Routing in the DTN is still an open issue currently. Further investigations, therefore, should continue.

2.5 Summary

In this chapter, the background and concepts of the DTN were given and elaborated upon. The DTN architecture is a bundle overlay running on top of multiple heterogeneous regional networks. Convergence layers provide an integrated interface between the bundle overlay and underlying networks. Different categories of mobility models and the most common routing algorithms in DTNs were also introduced. The performance of the DTN, which could be evaluated by message delivery rate and delay, is affected greatly by the mobility characteristics of nodes and routing algorithms. With the characteristics of intermittent connection and frequent disruption, the message delivery rate and delay of DTNs are often far from being satisfactory. In the next chapter, we will introduce the infrastructure nodes, which are called MRs, into DTNs to improve the network performance. We will discuss the requirements, architecture and communication process of the MR.

3 Message Repository

Message repositories are a set of DTN infrastructure nodes which create more contact opportunities and provide higher capacity in frequently partitioned networks. The main goal of introducing MRs in DTNs is to create more opportunities for message transfer, consequently enhancing the message delivery ratio.

3.1 Motivation

The DTN architecture and bundle protocol are developed to enable communications in challenged network environments and provide a common service on top of diverse regional networks. Message delivery of DTNs follows a store-carry-forward paradigm. Message transfer over DTNs only occurs at the time one mobile node appears in the radio coverage area of other nodes. The limited contact opportunities and insufficient capacity will decrease the message delivery rate and cause additional delivery latency. Therefore, we consider to introduce some infrastructure nodes in DTN networks to improve the message delivery ratio and shorten message delivery delay. The infrastructure nodes could create more contact opportunities and enhance the capacity of DTNs. Moreover, the infrastructure nodes act as rendezvous points for message storage and distribution. The infrastructure nodes with high capacity and Internet connectivity are called message repositories.

MR nodes can be either stationary in certain locations or mobile with a predefined schedule. Continuous or occasional Internet access are supported by MRs. MRs are expected to be applicable in multiple DTN scenarios and robust to improve data delivery rate. For example, we could deploy MRs in the remote and less-developed areas, where there might be no Internet connectivity for individuals. We can set MRs with infrastructure connection in the central area of each village. Residents in a village periodically come to the MRs, sending messages to the MRs and retrieving messages from the MRs via wireless connection. In this way, villagers could get Internet connectivity with low cost. Among neighbor villages, we can utilize the vehicle such as buses, to transmit messages between MRs. Hence, messages transfer between villages can be achieved. Another important DTN scenario is the urban scenario which we have discussed previously. Mobile users carry the devices which are enabled with a DTN messaging application. Mobile users create messages, including picture and video, and wait to send them to targeted destinations. However, mobile users may not quite frequently meet each other. It might take a long time for a message reaching its targeted destination. In order to increase the message delivery rate, we introduce MRs into the DTN urban area. MRs are often located in or mobile around the places where people frequently visit, such as shopping centers and parks. When mobile users connect to MRs, they are able to exchange messages via wireless connections. Moreover, when mobile users get home, they could also retrieve the messages, which are not delivered via DTNs, from MRs via Internet. Our simulation is mainly based on the DTN urban scenario [3].

3.2 Goals and Requirements

Basically, there are three main goals for the message repository design. The first and most important goal is to enhance the performance of DTNs, especially increase delivery ratio and decrease delivery delay. Secondly, with the infrastructure characteristics of the MR, it is possible to monitor DTN networks and mobile nodes. Thirdly, we expect that MR is flexible to be deployed in many different DTN scenarios and the implementation of the MR supports to be widely reusable [3].

A. Improve the Performance of DTNs

A message repository is an infrastructure node which provides continuous or occasional Internet connectivity. The MR will always keep messages in reliable storage. When more than one MR exists in DTNs, they could share messages in a database via the Internet. Although underlying routing protocols specify the message lifetime and maximum copies, the message repository could still hold the expired messages.

The message repository always sends advertisements which contain the current bundle list of the database. MR-aware nodes discover the MR, when they receive the advertisement. MR-aware nodes will interpret the advertisements and exchange their own bundle lists with MRs, then MRs and MR-aware nodes will exchange bundles which others do not have. The exchanged bundles can be transferred by normal DTN nodes, hop-by-hop, until they reach the targeted MR or MR-aware nodes. With the bundle exchange mechanism, MRs will obtain a great number of bundles and save them in storage. Therefore, when a mobile node contacts the MR, it can retrieve the bundles intended for itself. Thus, the MR also provides a bundle retrieval mechanism over Internet. If mobile nodes are available to access Internet, they could download undelivered bundles from the MR database.

B. Network Monitoring

An MR-aware node is capable of creating bundle traces and send them to MRs. Possible information included in the bundle traces could be transferred bundles, successfully delivered bundles or deleted bundles. MR nodes could provide a graphical user interface by which network information is shown directly and clearly.

C. Generic Applicability

A message repository should be deployed in both frequently connected environments such as urban scenarios and frequently disconnected environments such as rural scenarios. The implementation of the MR should be compatible with the DTN protocol stack currently in existence and widely adopted. The bundle exchange mechanism between MRs and MR-aware nodes should be independent of the underlying routing protocols.

3.3 Architecture

To illustrate the message repository architecture, we need to introduce the following components in the architecture [3].

A. Message Repository

Message repository nodes are the infrastructure nodes which generate and send repository advertisements. They also receive bundles and message traces from normal DTN nodes and MR-aware nodes. The MR utilizes the bundle protocol for communication and holds the shared bundles in a reliable database.

B. Repository Database

The function of the repository database is to store the shared bundles and message traces. The repository database may be together in the same device along with the MR or located remotely in the infrastructure network. The MR connects to the database using the TCP/IP protocol suite. If multiple MRs exist in the network, they could share a central database. We define the MRs that share one central database as a repository region.

C. Message Repository Client

The message repository client is a normal mobile node with the MR-aware function. It is just the MR-aware node we mentioned previously. The MRC is capable of interpreting repository advertisements and exchanging bundles with MRs. The exchange of the bundles follows a particular communication procedure which extends the forwarding policies and complements the DTN routing protocols.

D. Normal DTN Nodes

A normal DTN node transmits bundles based on the standard bundle protocol. Moreover, it can transfer repository advertisements and shared bundles between MRs and MRCs. A normal DTN node cannot understand the shared bundles and only acts as a relay for shared bundles delivery.

The message repository architecture is composed of the components above. Figure 3.1 shows the overview of the complete message repository system architecture.

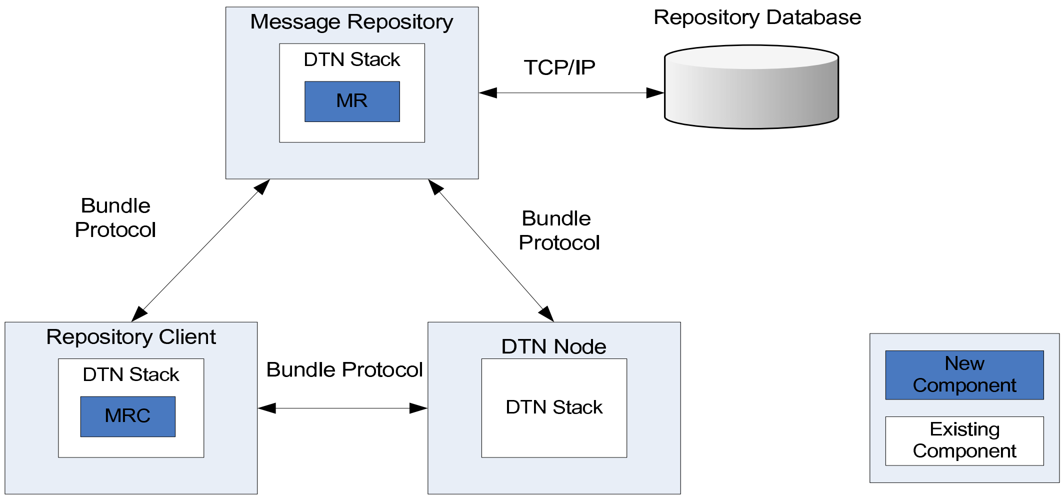


Figure 3.1: Architecture of Message Repository System

3.4 Communication Procedures

Message repositories discovery is realized by broadcasting repository advertisements to other DTN nodes. Message repository nodes can be stationary or mobile following a particular schedule. Once the link between an MR and other DTN node is up, the MR will send a repository advertisement. The repository advertisement is a broadcast bundle which contains the EID of the message repository. When an MRC receives the advertisement, the bundles exchange process between the MR and MRC will start.

Basically, there are single-hop forwarding and multi-hop forwarding approaches for the delivery of repository advertisements and exchange of bundles. In the single-hop forwarding case, repository advertisement delivery and bundle exchange only occur when MRs and MRCs directly connect to each other. In the multi-hop forwarding case, besides the directly connected situation, normal DTN nodes are able to relay repository advertisements and shared bundles between MRs and MRCs. The multi-hop forwarding will include the single-hop case when MRs and MRCs are directly connected.[3].

There are two alternatives for the bundle exchange mechanism of the multi-hop forwarding approach. The first alternative is to encapsulate the shared bundles into a standard bundle and transfer it via intermediate nodes to an MR. The destination address of the standard bundle is the EID of the MR and the payload of the standard bundle is the shared bundles. The intermediate normal DTN nodes and MRCs will relay the encapsulated bundle to the MR. Similarly, the MR follows the same procedure to create an encapsulated bundle and transmit it to the MRC. The disadvantage of this approach is that the encapsulated bundle in the payload might miss its final destination even if it is relayed by that node. The second alternative is to add a secondary destination address to the shared bundle. Normal DTN nodes cannot understand the secondary destination address of the bundle, only MRC nodes are able to interpret the secondary destination and deliver the bundle to the MR. This approach solves the problem that encapsulated bundles miss their targeted destinations on the way to the MR or MRC. For the single-hop forwarding approach, as MRs and MRCs could be directly connected, there is no need to utilizing the secondary destination address for bundle delivery. Shared bundles are encapsulated into a normal message and directly transferred between MRs and MRCs.

Bundle exchange can be achieved by either a four-step bundle exchange or a three-step bundle exchange. For the encapsulated bundle exchange approach, the four-step bundle exchange is: firstly, an MR generates a repository advertisement and sends it to an MRC, which, in turn, receives the advertisement and sends its bundle list. Then, the MR gets the bundle list and sends back a bundle containing its own bundle list and bundles not in the MRC. Finally, the MRC forwards a bundle including the bundles not in the MR. The four-step bundle exchange in encapsulation mode is shown in Figure 3.2. The three-step bundle exchange saves one-way exchange by including the MR bundle list in the repository advertisement. The MRC gets the advertisement and sends back a bundle containing its own bundle list and bundles not in the MR. The last step is the MR returning the bundles not in the MRC. For secondary destination bundle exchange, the differences lie in that: when either an MR or MRC gets a bundle list from each other, they will add the secondary destination address to the intended shared bundles. The three-step bundle exchange in encapsulation mode is depicted in Figure 3.3.

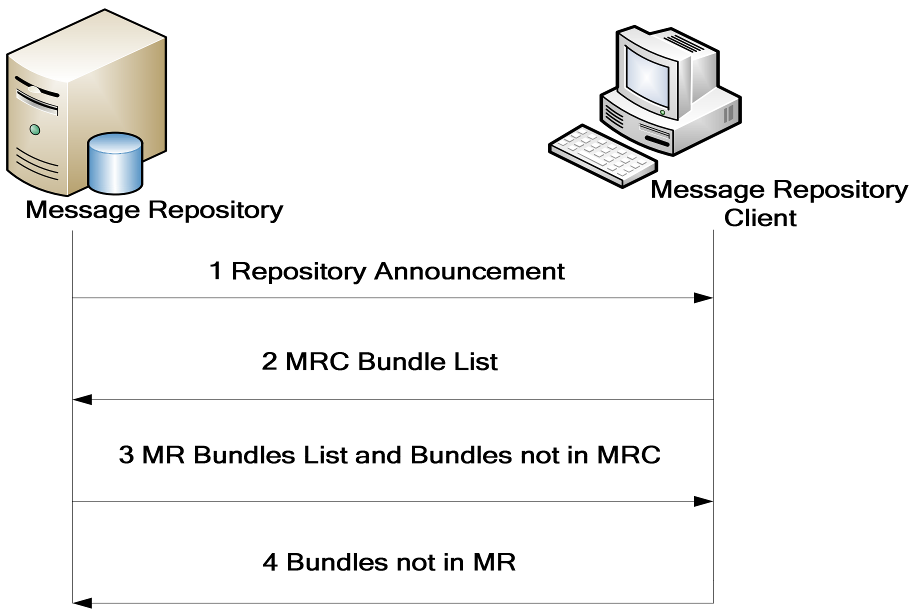


Figure 3.2: Four-step Bundle Exchange between MR and MRC

The three-step bundle exchange incurs fewer round-trip communications compared to the four-step bundle exchange process. However, with an increasing number of bundles being collected into the MR database, the size of the MR bundle list becomes larger. If the contact duration is long enough, there is no problem for completing the first flow of three-step bundle exchange. If not, for example, when mobile nodes quickly pass by, it might fail to forward the announcement with the MR bundle list to the next hop. The four-step bundle exchange separates the bundle list from the initial repository announcement. The size of the MRC bundle list is relatively small compared to that of the MR bundle list. Therefore, with four-step bundle exchange, it is more easier to transfer and distribute the repository announcement and MRC bundle list in the multi-hop case.

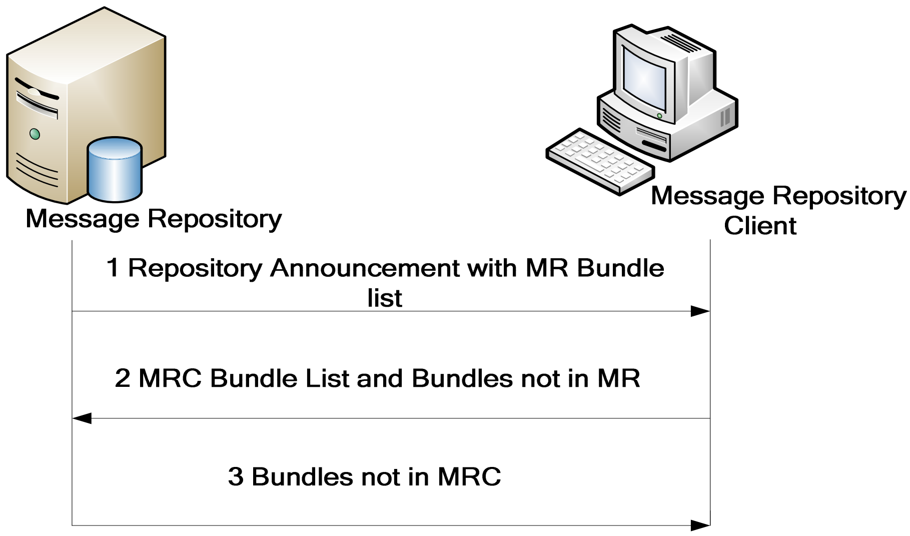


Figure 3.3: Three-step Bundle Exchange between MR and MRC

MR-specific messages such as repository advertisements and MR bundle list messages are needed to be frequently refreshed according to the changes in the MR database. For example, when new messages are saved into the database, the repository advertisements should include them in the bundle list. The repository advertisement broadcast will guarantee the frequently updating requirement for the MR-specific messages. Every time mobile nodes connect to MR, they will get a newly updated advertisement. However, it might cause excessive overhead in DTNs. In the multi-hop message delivery, the MR-specific messages involved in the bundle exchange process are transferred by multiple intermediate nodes, which might occupy large buffering capacity. To reduce the overload, we could control the number of MRC-enabled nodes and the lifetime of the MR-specific messages.

We could also choose to initiate the bundle exchange process by a message repository client instead of broadcasting the repository advertisements. It is a new MR discovery solution. We expect to reduce the MR-specific messages generated by the multi-hop approach. With this approach, we skip the multi-hop case and only focus on the single-hop situation. In the client-initiated approach, we assume that: besides MRs, there are some other infrastructure nodes, such as access points, in DTNs. We also assume the mobile nodes know how to access the Internet and connect to MRs via access points. When an MRC connects to an access point, it will get the Internet access. As MRs are connected to the Internet as well, they could exchange their respective EIDs and implicitly create a routing table entry. Thus, the MRC could send an initial contact request to the MR with a single hop in DTNs. The following bundle exchange procedure is completely the same as that of the three-step bundle exchange in encapsulation mode. Figure 3.4 depicts the message flows between the MR and MRC. If the MR and MRC are directly connected via WiFi radio, they will also exchange bundles following the three-step bundle exchange in encapsulation mode. MR-specific messages will never be relayed and forwarded by intermediate nodes. Moreover, we set a short timeout value for MR-specific messages in the client-initiated query case to guarantee frequently updating the repository bundle lists. Furthermore, when normal mobile node connects to the access point, it could also retrieve bundles from the MR via the bundle protocol. The query-based approach is an optimal alternative for the bundle exchange process regarding reducing the traffic overhead in practical deployment.

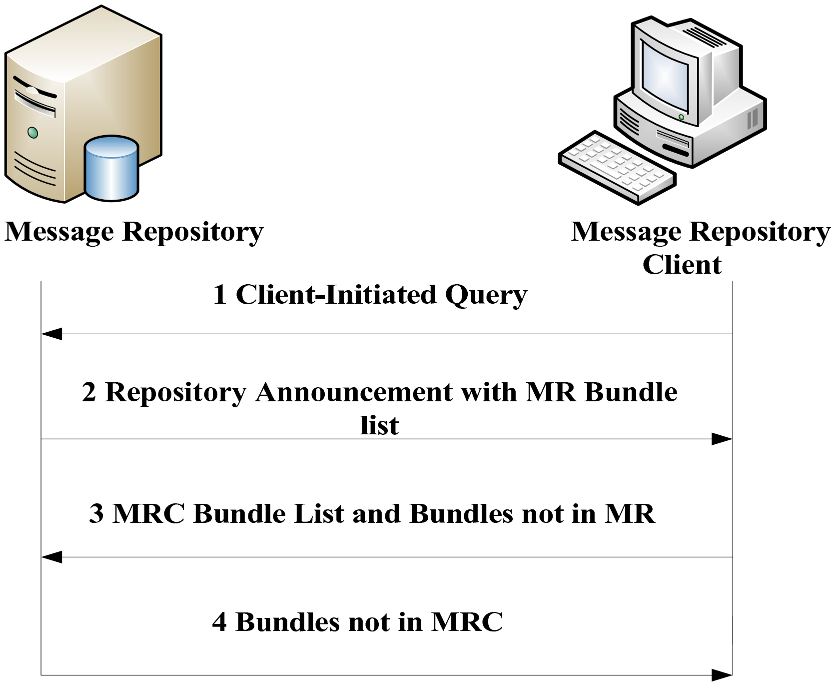


Figure 3.4: Client-Initiated Approach for Bundle Exchange

3.5 Implementation

The implementation of the message repository and message repository client is by extending the DTN2 stack, which was done by the people from Nokia Research Center. The MR and MRC are both implemented as the internal modules of the DTN2 stack. New modules interact with the existing modules (Bundle Daemon and Bundle Actions) in DTN2. The MR interacts with the repository database by an event-trigger. The trigger events are BUNDLE RECEIVED, BUNDLE TRANSMITTED, BUNDLE EXPIRED and CONTACT UP. Currently, the single-hop discovery and forwarding only have been partially implemented. Figure 3.5 shows the main components of the modified DTN2 stack [3].

A messaging service is also implemented together with message repository. It includes a PHP web server and a native DTN application for message sending and receiving [3][28].

In the thesis, we never emphasize the issues related to the real-world implementation of MR. We only focus on evaluating the MR performance by means of simulation.

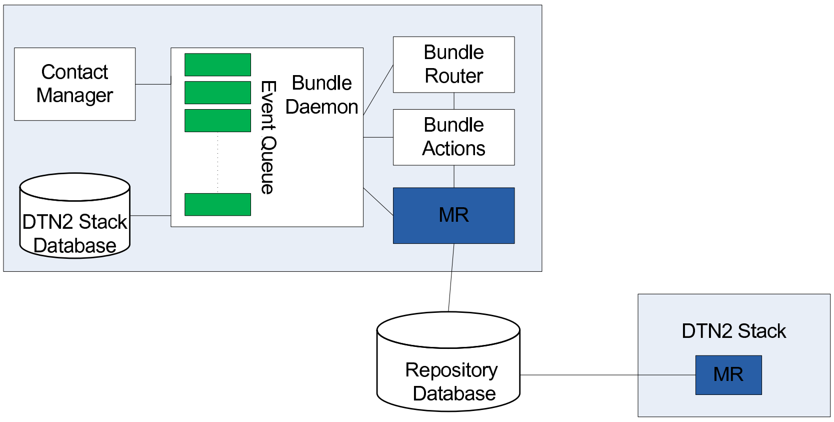


Figure 3.5: Main Components of MR

3.6 Summary

In this chapter, we described the message repository, which is desired to enhance the performance of DTNs. We discussed the motivation and requirements for the MR scheme. We proposed the MR architecture and communication procedures. Currently, only the single-hop case for the message repository has been implemented. We plan to test the performance of the MR by means of simulation. In the next chapter, we will introduce the technology and tools utilized in our simulation.

4 The Opportunistic Network Environment Simulator

In this chapter, we will give a general introduction of the Opportunistic Network Environment simulator, which can be simply called the ONE simulator. With the ONE simulator, the performance of the message repository is simulated under various routing protocol environments.

4.1 Software Architecture

The ONE simulator is implemented in Java, the core component of it being an agent-based discrete event simulation engine. It includes various modules, such as movement models, routing, event generator, visualization and results reports. Simulation runs based on a certain time step. These modules interoperate with each other and update every simulation time step. The ONE simulator is capable of generating mobility traces and simulating opportunistic connections with real-time visualizing features. Figure 4.1 shows an overview of the ONE simulator [29].

4.2 Mobility Modeling and Routing

The most common movement models utilized in the ONE simulator are the random waypoint model, map-based model (MBM), shortest path map-based movement model (SPMBM) and route-based model. The SPMBM is a more advanced version of the MBM, which uses Dijkstra's shortest path algorithm to decide the shortest path to the destination. Both MBM and SPMBM models are widely utilized in real-world scenarios. Moreover, map data could include Points of Interest (POIs). Every POI belongs to a particular POIs group. A POIs group is always used to model the places which people frequently visit, such as tourist attractions, shops and restaurants. Mobile nodes can be configured with a certain probability for choosing POIs in a particular POIs group as the next destination. The route-based model is used for modeling nodes mobility following certain routes, such as buses and trams. Mobile nodes in the ONE simulator will move to one destination, wait for a specific time period then leave for the next destination [29][30].

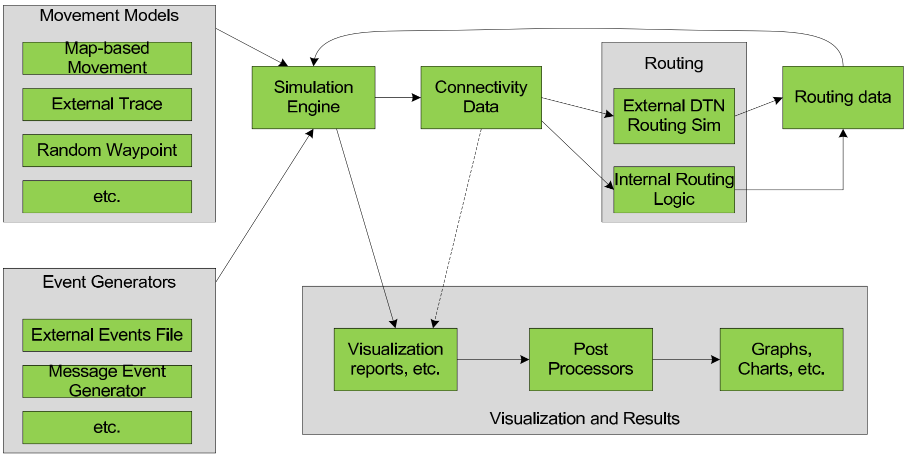


Figure 4.1: Overview of the ONE Simulator

The most common routing modules in the ONE simulator are direct delivery, epidemic, spray and wait (normal mode and binary mode), PRoPHET and MaxProp. The ONE simulator also supports a passive routing module which can be utilized as an interface to import message routing from other DTN simulators [29].

4.3 Reporting and Visualization

The ONE simulator provides various reporting modules which are able to collect the statistics of message delivery rate, message delivery delay, the inter-contact times of nodes, etc. These statistics facilitate us to analyze the performance of the network [31].

Simulation can be visualized by the Graphical User Interface (GUI). Nodes mobility, link going up and down, and message delivery are displayed in the GUI. With the GUI, users can get an overview of what simulation is in progress.

4.4 Application Support

The ONE simulator provides a message generation module to generate application-specific messages. The application-specific attributes can be attached to the message by key-value pairs. The mobile nodes enabled with a certain application could interpret the key-value pairs and give reaction following the predefined rules [31].

The message repository is implemented by adding application-specific attributes to the message header. The MR-specific attributes are categorized into advertisements, bundle list, bundle encapsulation and secondary destination. It is possible for one message to have more than one attribute. When MR nodes or MRC nodes receive the MR-specific messages, they will handle messages following the predefined message exchange procedure, which was discussed in Chapter 3. In the three-step bundle exchange in encapsulation mode, for example, an MR will send a repository advertisement with a bundle list when a link is up. When an MRC receives the repository advertisement, it will compare the bundle list and bundles in its own storage, then encapsulate the bundles missing in the MR into a single message. The MRC forwards the message together with its bundle list. We set the maximum number of encapsulated bundles to ensure the message is not too large for delivery. If the number of desired bundles exceeds the limitation, the encapsulated bundles will be chosen randomly among the desired ones. When the MR receives the message from the MRC, it will save the missing bundles and send back the bundles desired by the MRC in an encapsulated message. Finally, the MRC will get the message and save the missing bundles into its buffer.

In secondary destination mode, the only difference is that MR or MRC nodes will mark the missing bundles with a secondary destination address instead of encapsulating them. The bundles with a secondary destination address are delivered as normal messages. Only MRs and MRCs are able to understand the secondary destination address. When secondary destination address-aware nodes meet, they will retrieve the bundles with the secondary destination, which are targeted to themselves.

In the client-initiated approach, we introduce some access point nodes with continuous Internet connectivity. When MRC nodes connect to the access point, they will get a specific EID of a MR. Thus, MRCs could send the initial query to the MR via Internet like there is only a single hop in between at the bundle layer. Similarly, when MRCs directly connect to MR, they will also initiate a query to start the bundle exchange process. The following bundle exchange procedure is completely the same as that of the three-step bundle exchange in encapsulation mode. In addition, we limit the MR-specific message exchange only occurring in single-hop situation in the client-initiated approach. This could reduce the MR-specific messages generated in multi-hop approach.

MR nodes will periodically delete the old repository advertisements. As there is limited capacity of mobile devices in DTNs and the information carried in MR-specific messages needs to be updated frequently according to the changes in the database, the lifetime of MR-specific messages will be shorter than that of normal messages. All MRs in an area will share a central database. The database provides reliable storage and always keep a copy of the bundles even if the bundles might be timeout according to the underlying DTN routing protocol.

4.5 Summary

In this chapter, we introduced the ONE simulator and the message repository extension based on it in general. We will utilize the ONE simulator to simulate the operation of the MR. Next we will come to the practical simulation work in Chapter 5.

5 Simulations

In this chapter, we will evaluate the message repository design by the ONE simulator. We are interested in how much the performance of the network will be improved by introducing MRs into an urban scenario.

5.1 Simulation Environment Settings

In an urban scenario, it is assumed that mobile users communicate with each other by mobile devices which are enabled with a message repository client. As the storage of mobile device could be occupied by other useful data, the free buffer size of the mobile devices for DTN messages is assumed to be 100 MB for each user. Mobile users move around the city, generating and forwarding messages that could be pictures or videos. The size of the messages is assumed to be 500 KB-4 MB, following a uniform distribution. Mobile users generate messages for random destinations, message generation rate being 10-20 s/per message, using a uniform distribution. There are two categories of messages involved in transmission. One is normal message with timeout value of 5 hours. The other is MR-specific message with timeout value of 45 minutes, which is much less than that of normal messages. This is to avoid consuming too much buffer resource. Users are assumed to travel in the area by car or on foot during the daytime. A day is defined to last for 12 hours (approximately 43000 seconds), for example from 8:00 to 20:00. When a day ends, all users will get home and have Internet access. The normal message gather into the MR database could be kept for 12 hours. which could guarantee that messages undelivered in DTNs be retrieved from MR database via Internet. According to the message generation rate, the total number of generated messages in one day is approximate 3000. Hence, the maximum capacity demand for the repository database will not exceed 12 GB (3000×4 MB). It is not quite difficult to provide a database with a 12 GB of capacity. Therefore, we assume there is no strict capacity limitation for the central repository database.

The basic size of message repository advertisement is assumed to be 10 KB. The size of bundle list that may additionally be included in advertisement is in direct proportion to the number of bundle entries in the list. We assume the size of each bundle entry is 1 KB. We set the number limitation to 10 for the encapsulated messages in the payload in case contact duration is too short to complete the message delivery.

The part of the Helsinki downtown area (4500×3400 m) was chosen for our simulations. A general overview of the area is depicted in Figure 5.1. The orange lines stand for the roads, and black lines indicate the main roads which go through the central area. Some parks, shopping malls and tourist attractions are added into the map as POIs. The three brown points in the west are the tourist attractions. The four purple points in the north represent shops and, finally, the three blue points in the south stand for parks. In total, there are 130 mobile nodes moving in the downtown area. These nodes are divided into five groups, from which four groups are pedestrian groups. Pedestrians move at random speeds of 0.5-1.5 m/s and pause for 300-400 s every time they reach a destination. Therefore, when MRCs meet MRs, the pausing duration is long enough for completing message exchange process. The remaining one group is the car group including 10 nodes. Car node moves at the speeds of 10-50 km/h with a pausing time of 300-400 s. All random variables comply with a uniform distribution. The three pedestrian groups, which include 15 mobile nodes each, are distributed separately within three non-overlapping areas. Figure 5.2 shows the area segmentation. The remaining pedestrian group includes 75 mobile nodes which are distributed in the whole downtown area. Cars are able to travel to all the places in the map. All the mobile nodes, including pedestrians and cars, are permitted to travel on the main roads, to the shops, parks and tourist attractions. Message repositories are set in the places which mobile nodes visit with high probability, such as POIs and main road crossing points [19][31].

Figure 5.1: Helsinki Downtown Area

Figure 5.2: Three Areas Segmentation

We choose the MBM model for the pedestrian nodes and the SPMBM model for the car nodes. We define three POIs groups which represent shops, parks and tourist of interests. The pedestrian nodes choose POIs as destinations with an equal probability of 0.1 from the three POIs groups. Similarly, car nodes choose POIs as destinations with the equal probability of 0.2. We use the low power 802.11b WLAN (45 m range, 2 Mbit/s) for inter-connectivity between mobile nodes.

We focus on the most important goal how much will the message delivery ratio and delivery latency be improved by deployment of MRs in the urban scenario. We assume all the MRs belong to a single repository region. We evaluate the performance of the MRs in different bundle exchange processes. To avoid overloading the link capacity, we set the number limitation of shared bundles to be encapsulated into the payload. Moreover, it is assumed that MRs are constantly connected to the Internet. In this way, the central database could get immediately updated the moment any MR receives new bundles.

5.2 Performance Evaluation and Analysis

Five types of message repositories (MRs) are involved in the simulations, including three-step message exchange with messages encapsulation (MR3), four-step message exchange with messages encapsulation (MR4), three-step message exchange with a secondary destination (MR3SD), four-step message exchange with a secondary destination (MR4SD) and client-initiated query (MRCI). We utilize message delivery delay, message delivery latency and buffer occupation ratio, as performance metrics in our evaluation [32][33].

5.2.1 Stationary Message Repository Case

In this case, the message repositories are in fixed locations at the POIs and main roads. The location of MR nodes is shown in Figure 5.3. As the number of MRs increases from 1 to 15, Figures 5.4 to 5.13 show the message delivery ratio and delay of MRs under different routing protocols, including epidemic routing, SAW routing in binary mode with 10 initial copies and PRoPHET. The number of message repository client nodes is fixed to 30. The number of MRC nodes chosen from different groups complies with the proportion of the group nodes number. Buffer size of all the mobile nodes is 100 MB, including normal mobile nodes and MRC nodes. For each combination, we run the simulations with seven different random seeds and get the average value as the results.

Figure 5.3: Location of Stationary Message Repositories

Summarized from Figures 5.4 to 5.6, MR3SD shows higher delivery ratio than the other three. The message repository with a secondary destination holds a much better message delivery rate than that with messages encapsulation. The three-step message repository yields better performance than the four-step one for both messages encapsulation mode and secondary destination mode. The growing speed of message delivery probability is fast at the beginning and then becomes slow as the number of MRs increases. As multiple message repositories are introduced, message delivery ratio is highly improved. Taking MR3SD under SAW routing for example, the message delivery ratio has almost increased to 0.88 with 15 message repositories, compared to 0.45 without message repository in the simulation scenario.

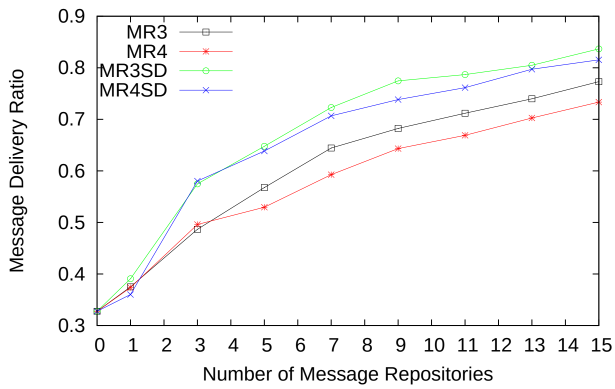


Figure 5.4: Message Delivery Ratio under Epidemic Routing

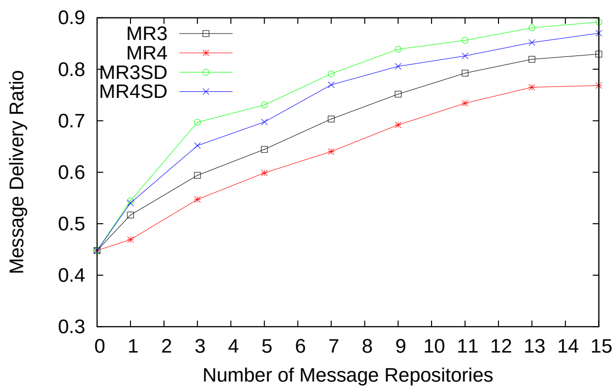


Figure 5.5: Message Delivery Ratio under SAW Routing

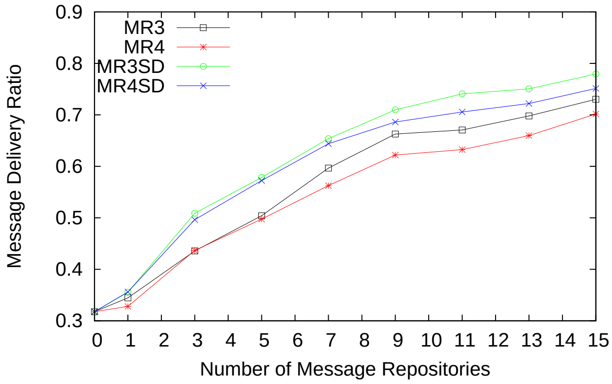


Figure 5.6: Message Delivery Ratio under PRoPHET

In Figure 5.7, Figure 5.8 and Figure 5.9, it can be observed that for all routing algorithms, message delivery delay will firstly increase and reach its peak when the number of message repositories equals 3, then drop down slowly with any further increases to the number of MRs. To analyze the delay, we will refer to the message delivery pattern of the message repository in Figure 5.10.

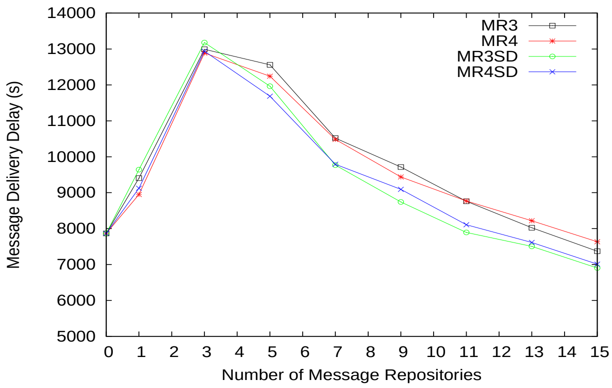


Figure 5.7: Message Delivery Delay under Epidemic Routing

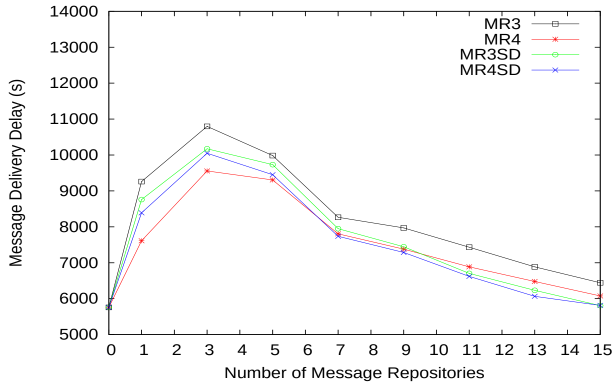


Figure 5.8: Message Delivery Delay under SAW Routing

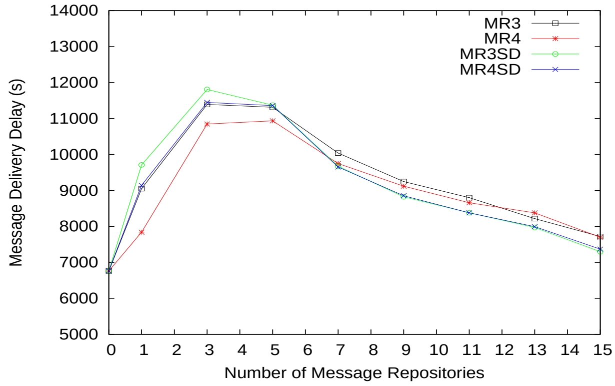


Figure 5.9: Message Delivery Delay under PRoPHET

Figure 5.10 shows the message delivery ratio curve of stationary MR3SD under the SAW routing algorithm. The number of MRs is set to 15 and the number of MRCs is 30. From the start to 43000 seconds, messages are transferred and delivered in the DTN network. The demarcation point is located at the time 43000 s which indicates the end of a day, mobile nodes get home and access the Internet to retrieve the targeted messages in the repository database. Therefore,a rapid increase is, naturally, to be seen at the time 43000 s. The message delivery latency is affected by the delay over DTNs and over Internet. The delivery delay over Internet is 43000 s which is a large constant value. The delivery delay of DTNs is a variable and relatively shorter compared to that of Internet. Therefore, when there are a great number of messages delivered over Internet, the delivery latency is likely to be high.

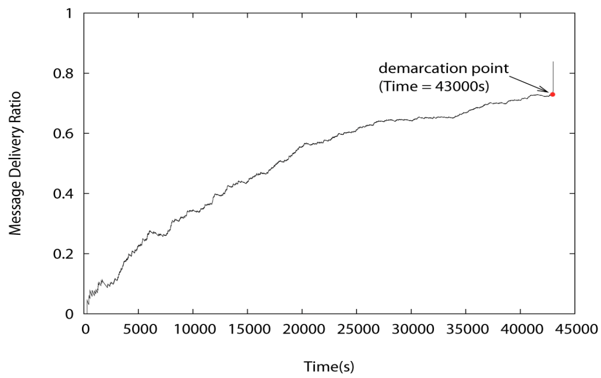


Figure 5.10: Message Repository Delivery Pattern

Figures 5.11 to 5.13 depict the ratio of message delivery over DTNs to that over Internet. The ratio of message delivery over Internet almost reaches its highest value when there are three message repositories in the scenario. With the number of message repositories further increasing, the messages delivery ratio over DTNs and total delivery ratio rise while the message delivery ratio over Internet decreases. As a result, the message delivery delay drops accordingly. It can be noticed that MR3SD performs best with the highest delivery probability and acceptable delivery latency under the three routing algorithms.

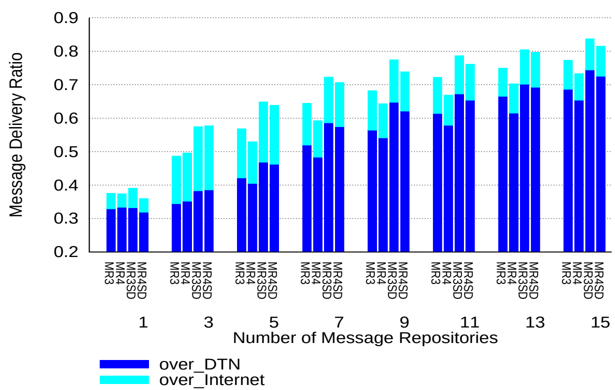


Figure 5.11: Message Delivery Ratio over DTNs and Internet under Epidemic Routing

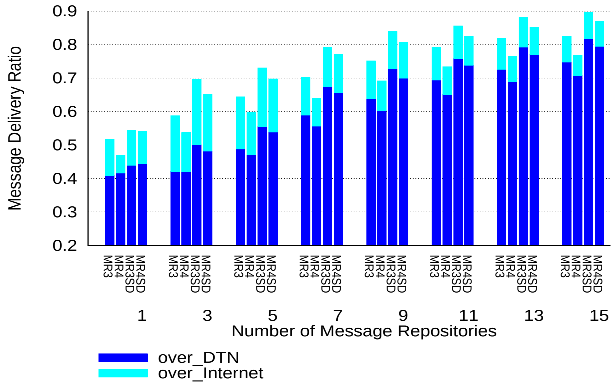


Figure 5.12: Message Delivery Ratio over DTNs and Internet under SAW Routing

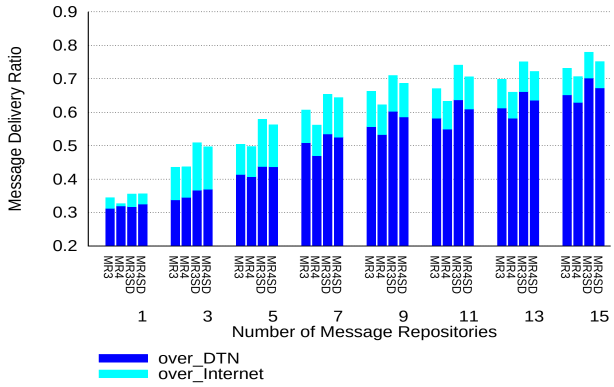


Figure 5.13: Message Delivery Ratio over DTNs and Internet under PRoPHET

From Figure 5.14 to Figure 5.16, we can summarize that message repository with the secondary destination mode consumes more buffer resource than that with message encapsulation mode, especially under epidemic routing as well as spray and wait routing. The reason could lie in that: in the message encapsulation mode, messages missing in MRs are encapsulated into a standard bundle. The intermediate DTN nodes will transfer this encapsulated bundle to the repository. However, in the secondary destination approach, messages are added with an additional, secondary destination addresses. Only MR and MRC nodes are able to interpret those addresses. There is a high possibility that each message with a secondary destination address has been replicated many time (depending on the underlying routing protocol). Multiple MRCs are possible to get those messages and forward them to the targeted MRs. It is similar to fragmenting the encapsulated bundle, replicating the segments, distributing them to MRCs and waiting to deliver them towards MRs. The timeout value of the encapsulated bundle is much shorter in comparison to that of normal messages with a secondary destination. Therefore, secondary destination mode will consume more buffer space than message encapsulation mode. This reflects the trade-off between resource occupation and network performance. The secondary destination approach achieves a high message delivery ratio and low delivery latency at the cost of more capacity occupation. Moreover, the message exchange in secondary destination mode appears in a distributed message sharing fashion, which is also possible for improving the message delivery ratio.

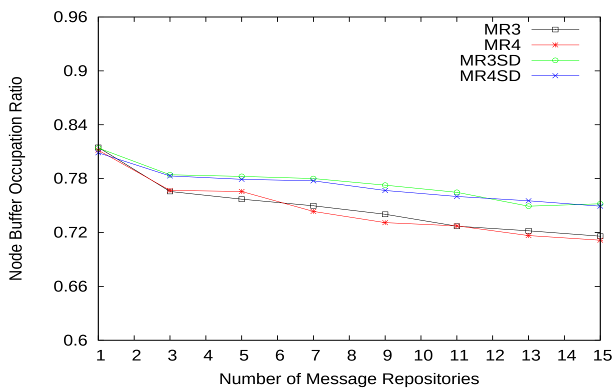


Figure 5.14: Node Buffer Occupation under Epidemic Routing

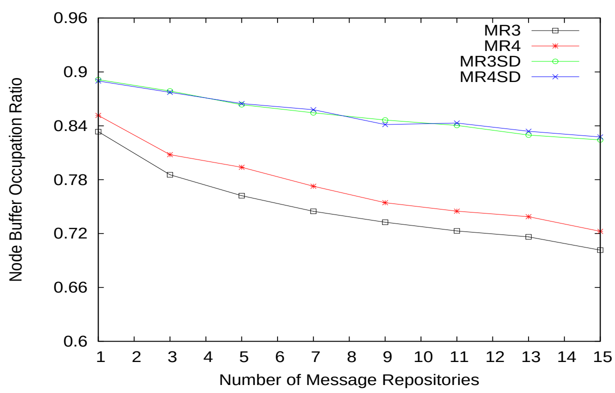


Figure 5.15: Node Buffer Occupation under SAW Routing

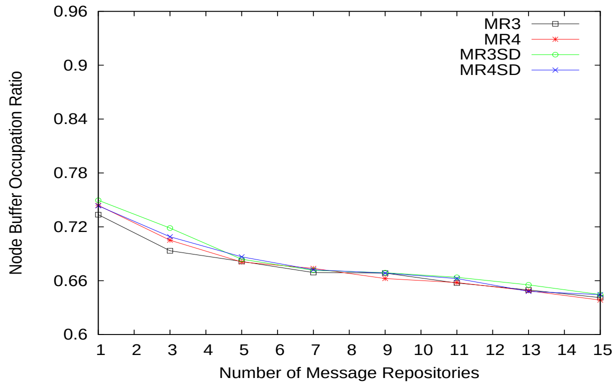


Figure 5.16: Node Buffer Occupation under PRoPHET

5.2.2 Mobile Message Repository Case

In this case, the message repositories are set to be mobile compared to the stationary MRs case. The mobility of the message repositories follows the MBM model. The mobile paths for the MRs are the main roads and POIs. Other settings are the same as those for the stationary case. We show both stationary and mobile cases in the same graph for purposes of comparison. Figures 5.17 to 5.20 show that stationary message repositories yield a higher message delivery rate than mobile message repositories regarding all types of MRs under the three routing algorithms. Another interesting finding is that the highest delivery ratio is always achieved when MRs are utilized under the spray and wait routing algorithm.

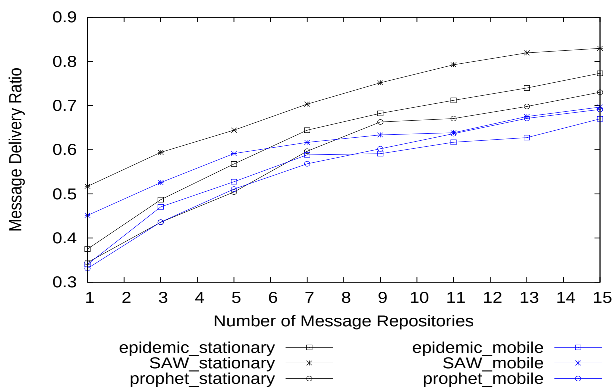


Figure 5.17: Message Delivery Ratio of Stationary and Mobile MR3

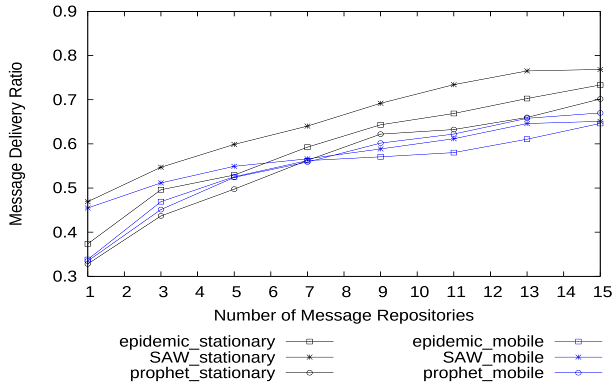


Figure 5.18: Message Delivery Ratio of Stationary and Mobile MR4

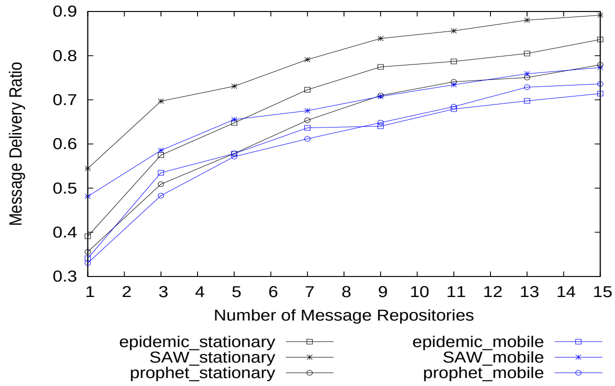


Figure 5.19: Message Delivery Ratio of Stationary and Mobile MR3SD

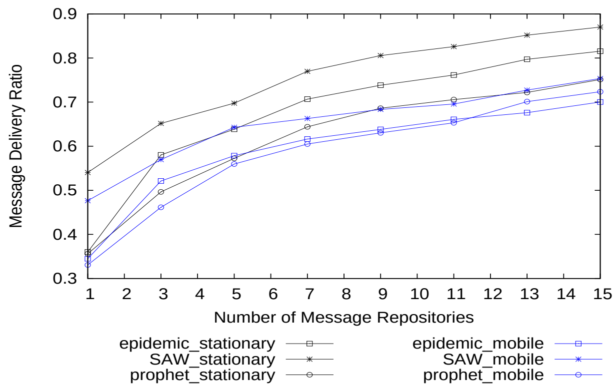


Figure 5.20: Message Delivery Ratio of Stationary and Mobile MR4SD

With epidemic routing, excessive duplicated copies of messages, both normal messages and MR-specific messages, are generated and relayed in DTNs, which consumes much buffer resources and degrades the DTN network performance. On the other hand, when normal node connects to the message repository, the node will forward the messages to the MR by flooding. In this way, the MR could gather a great number of messages into the database and wait to deliver them to the targeted hosts when conditions permit. That is why the message delivery ratio over Internet is always high under epidemic routing. In PRoPHET routing, a normal DTN node is not necessary to treat MR nodes as the next hop to forward the messages, as the MR may not hold a higher prediction for meeting the intended destination than the normal node. Therefore, except exchanging messages with the MRC, the MR could not collect that many messages from normal DTN nodes as it does under epidemic routing. Spray and wait routing provides a compromised solution. It does not consume too many resources, but gives a high possibility for normal nodes forwarding messages to MRs. As a result, SAW routing yields satisfying delivery ratio and acceptable delivery delay via both DTNs and Internet.

5.2.3 Effect of Message Repository Client Density

We fix the number of message repositories to 9 and explore the effect of message repository client density on message delivery ratio and delay. It is to be seen from Figures 5.21 to 5.26, that the message delivery ratio performs best when the number of MRCs is 30. The only exception is MR4 under epidemic routing and SAW routing. The message delivery delay keeps rising with the number of MRCs increasing for all types of MRs and routing algorithms. Similar to the results of the stationary MR case, MR3SD shows the best delivery ratio. The message repository with a secondary destination holds a much better message delivery chance than that with message encapsulation. The three-step message repository yields better performance than the four-step approach for both messages encapsulation mode and secondary destination mode.

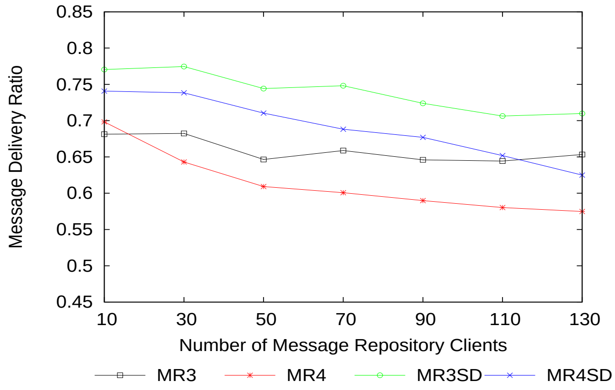


Figure 5.21: Message Delivery Ratio with MRCs number variation under Epidemic

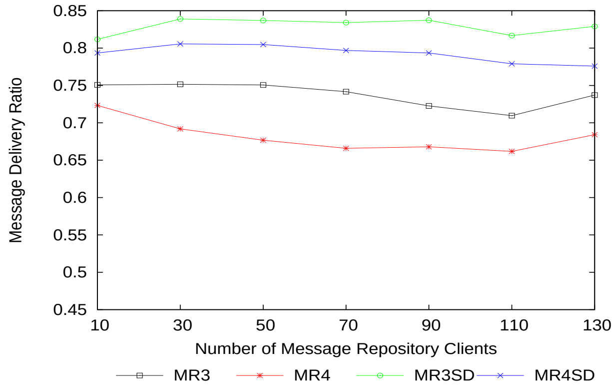


Figure 5.22: Message Delivery Ratio with MRCs number variation under SAW Routing

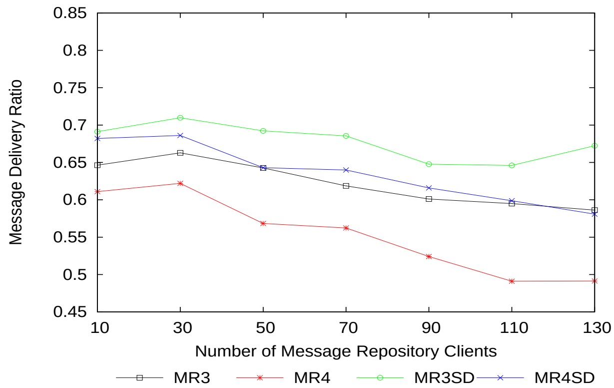


Figure 5.23: Message Delivery Ratio with MRCs number variation under PRoPHET

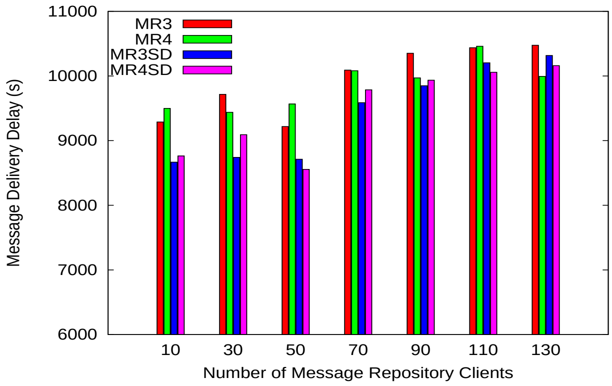


Figure 5.24: Message Delivery Delay with MRCs number variation under Epidemic Routing

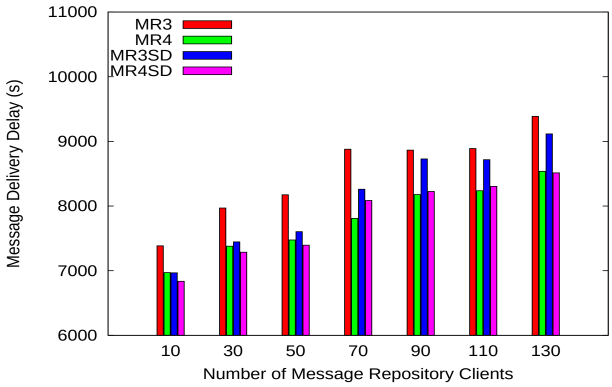


Figure 5.25: Message Delivery Delay with MRCs number variation under SAW Routing

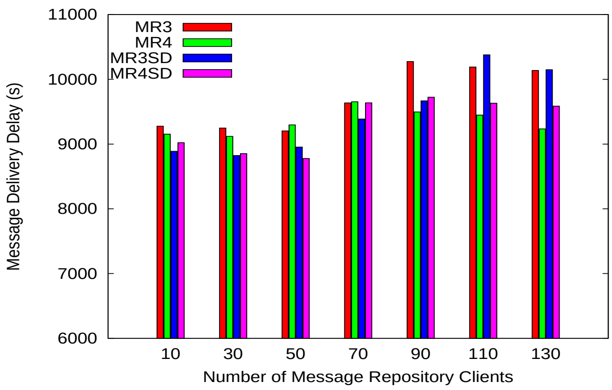
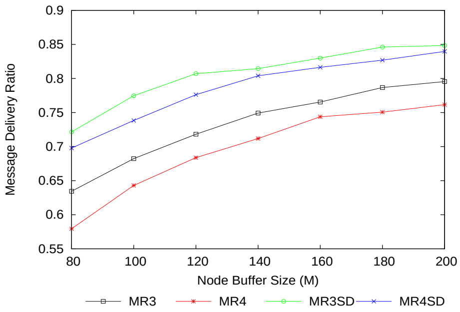


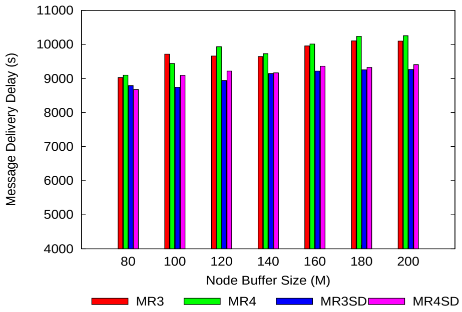
Figure 5.26: Message Delivery Delay with MRCs number variation under PRoPHET

5.2.4 Effect of Node Buffer Size

We set the number of MRs to 9 and MRCs to 30, then vary the node buffer size from 80MB to 200MB to analyze the impact on delivery ratio and delay. It appears

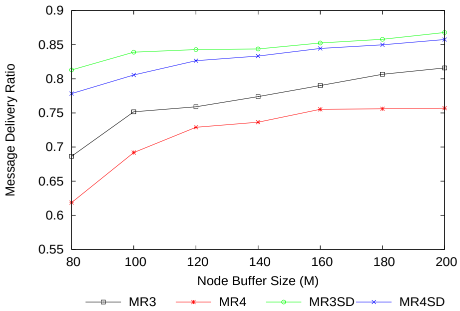


(a) Delivery Ratio

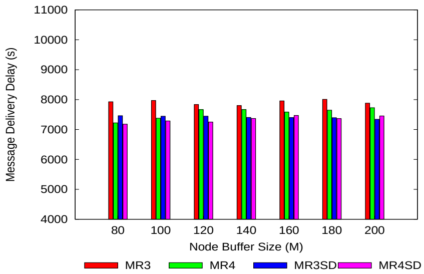


(b) Delivery Delay

Figure 5.27: Epidemic Routing with Node Buffer Size Variation

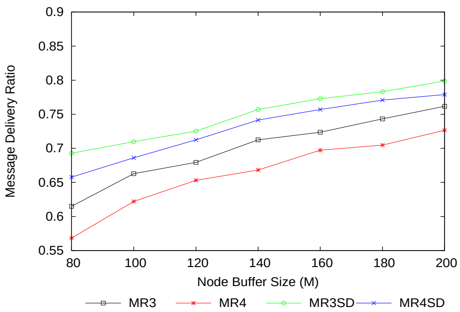


(a) Delivery Ratio

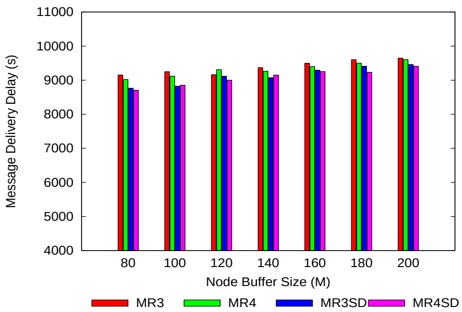


(b) Delivery Delay

Figure 5.28: SAW Routing with Node Buffer Size Variation



(a) Delivery Ratio



(b) Delivery Delay

Figure 5.29: PRoPHET Routing with Node Buffer Size Variation

that the increase of nodes' buffer size yields an improvement in message delivery rate. Especially when MRs are deployed under SAW routing, it displays a trend of reduced delivery latency and increasing delivery ratio. As is to be seen from Figures 5.27, 5.28 and 5.29, MR3 and MR4 appear more sensitive to the buffer size variation than MR3SD and MR4SD. MR3SD still performs with the highest quality in delivery rate. Moreover, MR3SD running under the SAW routing algorithm shows an increasing delivery ratio and decreasing delivery delay with buffer size augmenting.

5.2.5 Client-Initiated Approach for Bundle Exchange

In this section, we will investigate MR scheme with the client-initiated request approach. From previous simulation results, we obtained that the MR performs best in the stationary case under the spray and wait routing algorithm. Therefore, we utilize the client-initiated method under the same environment settings as that of the stationary MR case, using the spray and wait routing algorithm. We fix the number of MRCs to 30 and vary the number of MRs from 0 to 15. The locations of MR are also totally the same as that in stationary MR case. We will investigate the delivery ratio, delay and node buffer occupation of the DTN network. There are 10 access points randomly distributed in the simulation area. Figure 5.30 shows the location of the access points. We set the lifetime of MR-specific messages to 10 minutes. Therefore, frequent timeout messages will free the occupied buffer resources and guarantee the updating of the bundle list information.

In Figures 5.31 and 5.32, we could observe that the client-initiated approach yields a much higher delivery rate than MR3 and MR3SD. Meanwhile, the average message delivery delay is reduced by thirty percent compared to MR3 and MR3SD. Especial-

Figure 5.30: Location of Access Points

ly, when there are 15 MRs utilized in the DTN network, the delivery latency of the client-initiated approach almost decreases to 4000 seconds (approximately 1 hour).

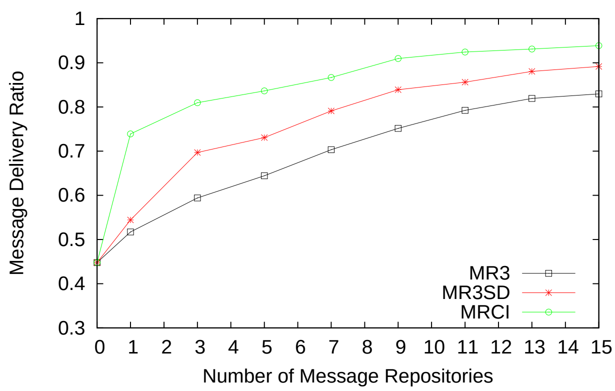


Figure 5.31: Message Delivery Ratio using Client-Initiated Approach

Figure 5.33 shows the node buffer occupation ratio of the three bundle exchange approaches. The client-initiated case consumes more buffer resources than MR3 and MR3SD. Basically, there are two categories of messages, MR-specific messages and normal DTN messages. In Figure 5.34, we could observe that the MR-specific message ratio is quite low in size towards the total messages in client-Initiated scenario. In contrast, MR-specific message ratio is much higher in MR3 and MR3SD scenarios.

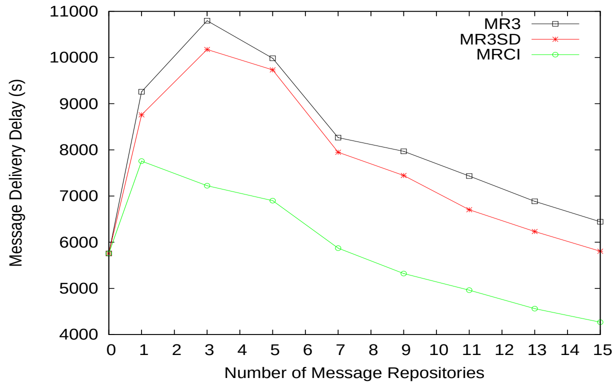


Figure 5.32: Message Delivery Delay using Client-Initiated Approach

Therefore, we could conclude that the node's capacity is mostly occupied by normal DTN messages in the client-initiated approach. In single-hop bundle exchange, the MR-specific messages are greatly reduced compared to the MR3 and MR3SD in the multi-hop cases. Normal DTN nodes could utilize more buffer resources and link capacity for saving and transferring targeted DTN messages. For instance, in the SAW routing, normal DTN messages could be widely distributed in mobile nodes. The newly introduced access points act as infrastructure nodes and create more opportunities for message delivery in DTNs.

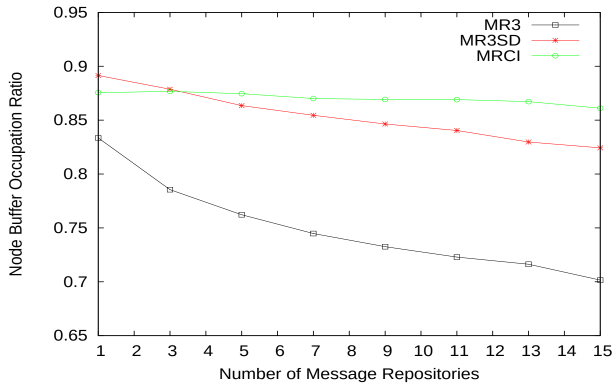


Figure 5.33: Node Buffer Occupation using Client-Initiated Approach

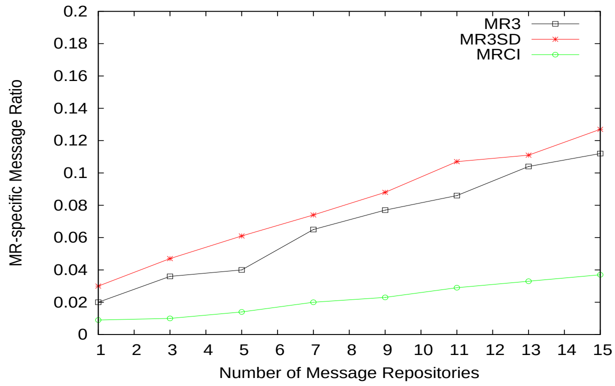


Figure 5.34: MR-specific Message Ratio

5.3 Summary

This chapter focused on the practical simulations. Through analyzing the simulation results, a great number of interesting findings were obtained. The results show that the message repository greatly improves the network performance especially in enhancing the delivery ratio and reducing the transmission latency. The stationary case of message repository performs better than the mobile case. The message repository with three-step exchange and secondary destination option shows the highest delivery ratio and acceptable delivery delay compared to the others. At the same time, MR3SD requires a relative larger buffer size for mobile nodes, which reflects the trade-off between the network performance and resource occupation. The simulation results also prove that it is not necessary to deploy the message repository client for each mobile node. Otherwise, it will consume too many resources due to excessive bundle exchange processes and degrade the delivery rate of the intended messages. The SAW routing algorithm provides more opportunities for normal mobile nodes to forward messages to MRs compared to PRoPHET. Furthermore, it does not overload the network as much as epidemic routing. The client-Initiated approach overcomes the problem of advertisements flooding and excessive MR-specific messages generated in multi-hop case. It adopts access points and implements the single-hop bundle exchange to achieve efficient buffer usage and high delivery ratio.

6 Conclusions and Future Work

In this thesis, we proposed and introduced a message repository approach for DTNs. The main contribution of this thesis is that: we evaluated the performance of DTNs with the message repositories by means of simulation. We justified our conclusions under various simulation parameters and different routing algorithms.

Message repositories act as infrastructure nodes in DTNs, aiming to enhance the network performance by increasing contact opportunities and storage capacity in challenged environments. Message repositories exchange bundles with message repository clients following a predefined procedure and save bundles in a reliable database. Multiple message repositories could share one database. Message repository delivers bundles to mobile nodes over DTNs or over Internet. The DTN network integrated with the message repository is cost effective and achieves better performance than a normal DTN network. The message repositories scheme does not change the underlying routing algorithm but provides a complement to existing routing protocols.

The performance of the message repository was evaluated by means of simulation. The simulation scenario is based on urban environments with pedestrians and cars. People move following regular routes and transfer messages when they interconnect with others. Message repository nodes are set in the main road crossings, or POIs, to model the places which people frequently visit, such as shops and parks. A certain number of mobile nodes are enabled with the message repository client. When MRs and MRCs encounter each other, they will exchange messages with each other. Moreover, MRC nodes will retrieve the messages intended for themselves from MRs. The message repository is capable of delivering messages over DTNs and over

Internet. People always receive messages over DTNs when they are mobile outside during daytime and retrieve messages over Internet when they reach home and get Internet access.

We ran the simulations with different types of message repositories and under different underlying routing algorithms. We varied the mobile node buffer size, the number of MR and MRC nodes, and implemented stationary and mobile MRs in our simulations. We also implement the client-initiated approach for bundle exchange only in single hop case. We were interested in the network performance evaluation, especially the message delivery probability and delivery latency. Summarized from the simulations results, we gained experiences and hints for optimal implementation and deployment of the message repository.

From the results of simulations, we observed that: the stationary message repository shows a higher level of performance than mobility cases with regard to both delivery ratio and delivery delay. MR3SD performs best with the highest delivery ratio and acceptable delivery delay compared to the other three. At the same time, MR3SD requires a relative larger buffer size for mobile nodes, which reflects the trade-off between network performance and resource occupation. It was also observed that it is not necessary to deploy the MRC for every mobile node. All types of message repositories achieve their best performance under the binary SAW routing algorithm. The client-initiated approach with single-hop bundle exchange makes great improvement of message delivery rate and highly reduces the excessive MR-specific message introduced by the multi-hop bundle exchange. This approach saves both node buffer resource and link capacity. The client-initiated query mechanism is an optimization option for the practical deployment of the message repository.

The thesis focused on the impact of the message repository on DTN network performance. Attention was not paid to the network monitoring characteristic of the message repository. The possible future work could focus on the network monitoring function of the MR. Furthermore, the statistics obtained the simulations are based on a certain number of assumptions, such as an abstract identical movement model for all mobile nodes and wireless radio coverage without obstacles. Due to this, the real-world deployment and testing of the message repository will be important for further evaluation.

Another further research direction could be the practical implementation of the message repository. Currently, only the single-hop implementation is partially implemented. The implementation of the single-hop and multi-hop approaches, will be carried out continuously. The security aspect of message repository will be taken into consideration. Security mechanisms should be added into the MR discovery and bundle exchange process to prevent malicious attacks.

Bibliography

[1] Stephen Farrell, Vinny Cahill, *Delay-and Disruption-Tolerant Networking.* 2006.

[2] The KioskNet Project, `http://blizzard.cs.uwaterloo.ca/tetherless/index.php/KioskNet`.

[3] Miaoqing Tan, Kari Kostiainen, Philip Ginzboorg, *Design and Implementation of Message Repository for Delay-Tolerant Networks (Draft).*

[4] Delay-Tolerant Networking Research Group, `http://www.dtnrg.org`.

[5] Wenrui Zhao et al., *Capacity Enhancement using Throwboxes in DTNs.* Proc.MOBIHOC 2006, October 2006.

[6] Wenrui Zhao et al., *A Message Ferrying Approach for Data Delivery in Sparse Mobile Ad Hoc Networks.* Proc.MOBIHOC 2004, May 2004.

[7] A.Seth et al., *Low-Cost Communication for Rural Internet Kiosks Using Mechanical Backhauls.* Proc.ACM Mobicom. September, 2006.

[8] V. Cerf, S. Burleigh, A. Hooke, L. Torgerson, R. Durst, K. Scott, K. Fall, H. Weiss, *Delay-Tolerant Networking Architecture.* RFC 4838, April 2007.

[9] S. Burleigh, K. Fall, et al., *Delay-Tolerant Networking: An Approach to Interplanetary Internet.* IEEE Communications Magazine, June 2003.

[10] Kevin Fall, *Delay-tolerant network architecture for challenged Internets.* Proc.SIGCOMM 2003, August 2003.

[11] Forrest Warthman, *Delay-Tolerant Networks (DTNs): A Tutorial.* 2003.

[12] W. Eddy, *Internet-Draft: Architectural Considerations for the use of Endpoint Identifiers in Delay Tolerant Networking.* 2006.

[13] Stephen Farrell, S. Symington, H. Weiss, P. Lovell, *Delay-Tolerant Networking Security Overview.* Internet-Draft, 2007.

[14] S. Symington, Stephen Farrell, H. Weiss, P. Lovell, *Bundle Security Protocol Specification.* Internet-Draft, 2007.

[15] K. Scott, S. Burleigh, *Bundle Protocol Specification.* RFC 5050, 2007.

[16] M. Demmer, J. Ott, *Delay Tolerant Networking TCP Convergence Layer Protocol.* Internet-Draft, 2009.

[17] T. Camp, J. Boleng, and V. Davies, *A survey of mobility models for ad hoc network research.* Wireless Communications and Mobile Computing 2, 5 (2002), 483-502.

[18] M. Musolesi, C Mascolo, *A Community based Mobility Model for Ad Hoc Network Research.* RealMAN 2006.

[19] Frans Ekman, Ari Keränen, Jouni Karvo, Jörg Ott, *Working Day Movement Model.* International Symposium on Mobile Ad Hoc Networking and Computing Proceeding of the 1st ACM SIGMOBILE workshop on Mobility models, May 2008.

[20] C. Perkins, Nokia Research Center, E. Belding-Royer, University of California, Santa Barbara, S. Das, University of Cincinnati, *Ad hoc On-Demand Distance Vector (AODV) Routing.* RFC 3561, July 2003.

[21] Evan P.C. Jones, Paul A.S. Ward, *Routing Strategies for Delay-Tolerant Networks.* 2006.

[22] J. Leguay, T. Friedman, V. Conan, *DTN Routing in a Mobility Pattern Space.* Proceedings SIGCOMM Workshop on Delay Tolerant Networks, 2005.

[23] A. Lindgren, A. Doria, *Probabilistic Routing Protocol for Intermittently Connected Networks.* draft-lindgren-dtnrg-prophet-02, March 2006.

[24] Amin Vahdat,David Becker, *Epidemic routing for partially connected ad hoc networks.* Technical Report CS-2000-06, Department of Computer Science, Duke University, April 2000.

[25] Thrasyvoulos Spyropoulos, Konstantinos Psounis, Cauligi S. Raghavendra, *Spray and wait: An efficient routing scheme for intermittently connected mobile networks.* In WDTN'05: Proceeding of the 2005 ACM SIGCOMM workshop on Delay-tolerant networking, 2005.

[26] John Burgess, Brian Gallagher, David Jensen,Brian Neil Levine, *MaxProp: Routing for vehicle-based disruption-tolerant networks.* In Proc. IEEE INFOCOM, April 2006.

[27] PRoPHET routing protocol, `http://prophet.grasic.net/`.

[28] DTN2 Reference Implementation, `http://dtnrg.org/wiki/Code`.

[29] Ari Keränen, *Opportunistic Network Environment Simulator. Special Assignment report.* Helsink University of Technology, Department of Communications and Networking, May 2008.

[30] Ari Keränen, Jörg Ott, *Increasing Reality for DTN Protocol Simulations, Technical report.* Helsinki University of Technology, Networking Laboratory, July 2007.

[31] Ari Keränen, Jörg Ott, Teemu Kärkkäinen, *The ONE Simulator for DTN Protocol Evaluation.* International Conference On Simulation Tools And Techniques For Communications, Networks And Systems Workshops Proceedings of the 2nd International Conference on Simulation Tools and Techniques, 2009.

[32] Earl Oliver, Hossein Falaki, *Performance evaluation and analysis of delay tolerant networking.* Proceedings of the 1st international workshop on System evaluation for mobile platforms, p.1-6, June 11-11, 2007, San Juan, Puerto Rico.

[33] Gnuplot, `http://www.gnuplot.info/`.